An Investigation of Drought in the Severn Trent Water Region: Re-evaluating drought severity, characteristics and generating mechanisms

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy

by

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Declaration

This dissertation is the result of my own work and includes nothing, which is the outcome of work done in collaboration except where specifically indicated in the text. It has not been previously submitted, in part or whole, to any university of institution for any degree, diploma, or other qualification.

In accordance with The University of Liverpool guidelines, this thesis does not exceed 100,000 words.

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Abstract

Drought is a recurring phenomenon resulting from natural climate variability; this hazard has multi-faceted impacts including on the economy, agriculture, public water supplies and the environment. Whilst there has been a resurgence in UK focused drought research since the 2010-12 drought, there is a wealth of understanding still required; particularly from a water resource planning and drought management perspective. This thesis seeks to increase our understanding of the drought hazard and its implications for water resources in the Severn Trent Water Region; located in the English Midlands and central Wales. A broad-scale understanding of drought is achieved through the analysis of meteorological, hydrological and groundwater variables using a standardised drought indictor approach.

A high resolution reconstruction of meteorological drought is accomplished using long series rainfall data from both newly reconstructed and extended rainfall datasets. This drought reconstruction allows the characterisation of notable droughts across the study region from 1858 to 2012, including the identification of the most severe events. This information is used in a water resource modelling framework to assess the impact of severe droughts identified prior to 1920 on a water resource zone yield to complement current water company planning documents. More recent meteorological droughts are examined for their spatial and temporal coherence to identify the potential impacts on water resources. This analysis identifies that the most severe droughts exhibit greater coherence across the study region resulting in more widespread water supply impacts. Analysis of hydrological and groundwater droughts identifies considerable variability in drought frequency, duration and severity within the jurisdiction of a single water company. This variability is primarily attributed to catchment storage properties and aquifer type. The investigation of the links between meteorological and hydro(geo)logical droughts reveals a complex relationship that provides useful insight for the development of drought monitoring systems. The potential for drought monitoring using drought indicators is also explored through the analysis of the links between large scale atmospheric circulation patterns and meteorological drought indicators. In the development of a detailed understanding of the drought phenomenon within the Severn Trent Water Region. This study develops an insight into the application of drought research for operational drought management; whilst the methods used throughout provide a generic framework to better understand this hazard.

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List of Abbreviations/Glossary

AMO	Atlantic Multidecadal Oscillation
BFI	Base Flow Index
BFIHOST	Base Flow Index derived using the Hydrology of Soil Types classification
CET	Central England Temperature
DO	Deployable Output
DP	Drought Plan
EA-WR	East Atlantic - West Russia
m^2/d	A unit of transmissivity- the rate that water is transmitted through the whole thickness and unit of the aquifer under a unit hydraulic gradient.
NAO	North Atlantic Oscillation
np-SPI	Standardised Precipitation Index calculated using a non-parametric method
NSWRZ	North Staffs Water Resource Zone
PCA	Principle Component Analysis
PDSI	Palmer Drought Severity Index
PE3	Pearson Type-III
PET	Potential Evapotranspiration
RIN	Rank Based Inverse Normal
SAAR	Standard Average Areal Rainfall
SDI	Standardised Drought Index
SGI	Standardised Groundwater Index
SPEI	Standardised Precipitation Evapotranspiration Index
SPI	Standardised Precipitation Index
SPI*max*	The SPI at the accumulation period that has the highest correlation coefficient with the SSI, SRI or SGI.
SRI	Standardised Reservoir Index
SSI	Standardised Streamflow Index
STR	Severn Trent Region
STW	Severn Trent Water
WRMP	Water Resource Management Plan
WRZ	Water Resource Zone

Overview of Severn Trent Water CASE Placement

A key component of CASE studentships is the requirement to spend between 3- and 18-months in a placement with the industrial partner. After my first year of research I spent 6-months based at Severn Trent Centre, Coventry working within the Water Resource Strategy Team. The purpose of this placement was to; (1) gain a better understanding of the water industry and the development of statutory planning documents (Water Resource Management Plans and Drought Plans), (2) better understand the needs of water managers, (3) familiarise myself with Severn Trent Water's water resource modelling and (4) obtain relevant data for the PhD thesis. During the placement I not only met the four objectives outlined above but assisted with a variety of tasks including making site maps and proofing reports. A key undertaking during the placement was the use their modelling framework to examine the implications of historic rainfall data in water resource yield assessments; this work included a detailed report to supply an audit trail and was the basis for a journal publication in Hydrology Research. Another key task was liaising with other employees across the company to access valuable datasets including historic reservoir level data which required digitising to enable its analysis in the thesis and at Severn Trent Water.

Chapter 1

Introduction

This chapter presents the aim and structure of this thesis and its context within current drought research.

1.1 Research Motivations

1.1.1 Drought: A Global Hazard

Drought is a truly global hazard, it is estimated that between 1900 and 2016 drought affected a total global population of over 2.2 billion people (EM-DAT, 2016). Often described as a 'creeping phenomenon' (Mishra and Singh, 2010) drought is a persistent natural hazard that can cover large areas over varying periods of time. It has multi-faceted environmental and socio-economic impacts, including agriculture, the environment, the economy, water resources and power production. Recent high-profile droughts include the multi-year drought in California (2011-16), with an estimated direct economic impact in the agricultural sector of 2.7 billion (US$) in 2015 alone, with 21,000 job losses in this sector (Howitt et al., 2015). In Australia, the 'Millennium Drought' (2001-2009), is considered the worst drought on record for the south-east of the country (Van Dijk et al., 2013). The impacts were severe and widespread including, frequent water restrictions, increased power prices, wildfires and decreased agricultural yields; between 2001 and 2008 cotton yields fell 83% (Heberger, 2012). South-east Brazil is currently experiencing a drought which has significantly impacted water supplies and power production. Cantareira Reservoir, São Paulo's primary reservoir, has been fluctuating at 5-15% capacity throughout 2015 (Seth et al., 2015). Much of mainland Europe experienced its worst drought in 2015, since 2003, with impacts including severe reduction in crop yields and disruption to riverine transportation (Van Lanen et al., 2016).

Drought is a recurring feature of natural climate variability, examples of severe drought can be found throughout human history. Historic droughts in the pre-instrumental period are identified in paleoclimatic studies using proxy data and documentary evidence. Helama et al. (2009) identify a multi-centennial mega-drought from the 9th to 13th Century across northern Europe. Multi-centennial mega-droughts have also been identified using proxy-data reconstructions in North America (Cook et al., 2007), Asia (Cook et al., 2010), east Africa (Russell and Johnson, 2005) and South America (Rein et al., 2004). More recently, devastating droughts occurred across the globe during the 20th Century. The 1930s Dust Bowl in the USA caused severe social and economic impacts with 3 million people migrating out of the US Great Plains (Seager et al., 2008). In north-western Europe the 1975-76 drought is attributed to substantial agricultural and economic impacts in the UK and France; with agricultural losses estimated at 500 million (GBP£) in the UK and in France milk yields were reduced by 25% (Sheffield and Wood, 2011).

There are many, varied definitions of drought, from the relatively simple through to the complex. The lack of a single precise and widely recognised drought definition may increase complexity in the understanding this phenomena, however drought definitions should to be specific to region, application or impact (Wilhite, 2000). Whilst there is no universal definition of drought 'a decrease in water availability in a particular period over a particular area' (Beran and Rodier, 1985) is a commonly used definition. Building on drought classifications outlined by Wilhite and Glantz (1985), Mishra and Singh (2010) outline five classifications of drought:

i. Meteorological drought is a precipitation deficit sometimes combined with increased evapotranspiration rates over a region for an extended period of time.

ii. Soil moisture/ agricultural drought is a reduction in soil moisture that limits soil water availability for plant/crops. This type of drought is often associated with crop failure. Soil moisture drought is driven by meteorological drought.

iii. Hydrological drought is a period surface water deficits in streamflow, lake and reservoir levels. Hydrological drought is driven by soil moisture drought and meteorological drought reducing inputs into surface waters.

iv. Groundwater drought is the reduction in groundwater recharge, groundwater levels and groundwater discharge. Groundwater drought is often over looked and included within hydrological drought (Sheffield and Wood, 2011).

v. Socio-economic drought is associated with the supply and demand of socio-economic goods that are impacted on by four drought classifications outlined above.

The links and interactions between the drought types outlined above are summarised in Figure 1.1. Drought remains a devastating natural hazard and despite an increasing body of drought research there is continued need to further understand all aspects of this hazard, from a processed based understanding, through to investigations on the social impacts of drought.

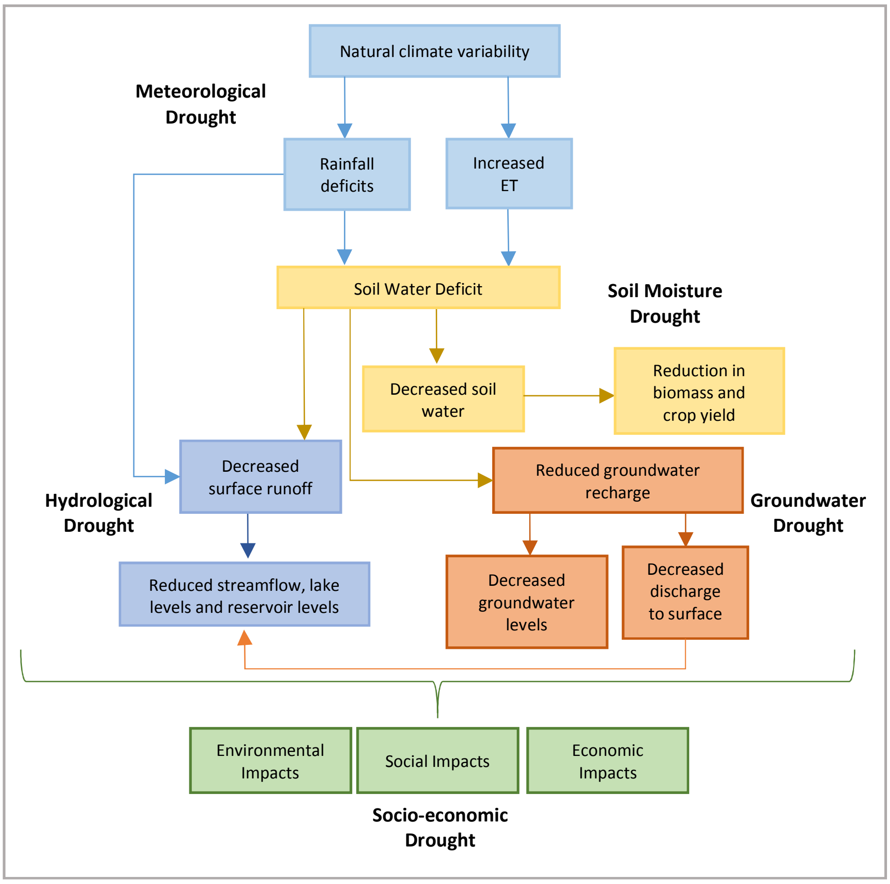

Figure 1.1: Schematic of drought types, their causes and links. Derived from the National Drought Mitigation Center, University of Nebraska-Lincoln
http://drought.unl.edu/DroughtBasics/TypesofDrought.aspx

1.1.2 Drought and Water Resources Management in the UK

Drought can occur in almost every climate zone on Earth (Mishra and Singh, 2010) and the UK is no exception to this phenomenon. A number of severe droughts have been experienced across the UK during the 20th and early 21st Centuries, including 1921-23, 1933-35, 1975-77 and 1995-96 (Marsh et al., 2007); these events caused numerous impacts including water supply disruptions and restrictions (Taylor et al., 2009). In the UK the impacts of the drought hazard tend to focus around economic losses, agricultural yield decreases and water supply disruption. For the general public, water supply restrictions during a drought are seen as an 'imposition' (Consumer Council for Water, 2010) and there is a general perception that droughts in water resource systems are a result of mismanagement by water companies rather than a consequence of natural climate variability (Waterwise, 2013). Whilst resource mismanagement can exacerbate drought impacts in water resource system (Bakker, 2000), managing the impacts of weather extremes (floods and droughts) remains a challenge for water managers (Brown et al., 2010). Both of these extremes were highlighted by the 2010-12 drought and its dramatic termination. The drought impacted much of England and Wales, with rainfall deficits during the winters of 2010-11 and 2011-12, which caused decreased streamflow, aquifer recharge and reservoir levels to such an extent that water use restrictions were imposed on 20 million people by April 2012 (Marsh et al., 2013). Within weeks of the introduction of water use restrictions, a change in synoptic patterns and shift in the Jet Stream resulted in a series of Atlantic fronts bringing copious rainfall; resulting in the highest April totals on record for England and Wales (1760-present; Marsh et al., 2013).

The 2010-12 drought, like past droughts, appears to have acted as a catalyst for continued understanding of this natural hazard, its impacts and management approaches. From a water resource perspective, the management of drought in the UK requires various advances including; (1) investigation of the potential for drought monitoring systems to improve early warning and preparedness, (2) improved understanding of the drought response in hydrological systems, and (3) the uptake of advances from drought science into drought management policy (CIWEM, 2012). However, progress in operational drought management in the UK is likely to require varying country dependant approaches. The provision of public water supplies in the UK is a rather fragmented affair. Whilst, water supplies in Northern Ireland and Scotland operate under a government owned structure, water supply provision in England and Wales is a privatised, state regulated industry. As a result of this privatisation and the devolution of environmental regulation within the countries of the UK, water resource management and drought planning structures vary. Within England and Wales there are currently 23 companies who provide water and waste water services (OFWAT, 2006; Figure 1.2a). Within this privately owned regulated industry structure, water companies in England and Wales are legally obliged to produce Water Resource Management Plans (WRMPs) and Drought Plans (DPs) to set out how they intend to manage water resources through a variety of possible scenarios, whilst differing structures are applied in Scotland and Northern Ireland. This thesis attempts to address some of the needs of water managers in England and Wales through an examination of meteorological and hydro(geo)logical drought within the jurisdiction of one water company; Severn Trent Water. Severn Trent Water supply water and waste water services to 7.5 million people across the English Midlands and central Wales (Figure 1.2b).

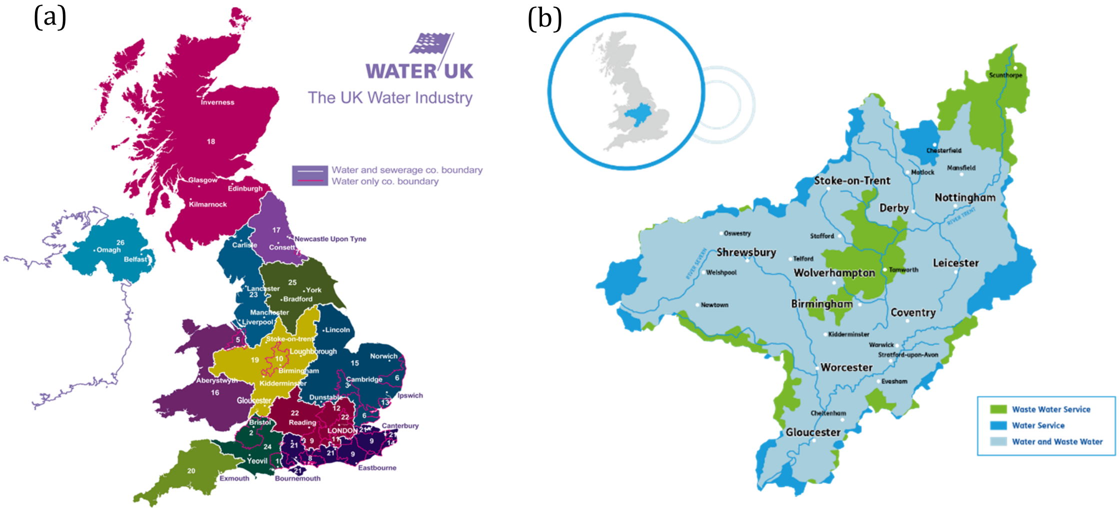

Figure 1.2: (a) UK water industry jurisdiction map. Source: Water UK http://www.water.org.uk/consumers/find-your-supplier, (b) Severn Trent Water Region. Source: Severn Trent Water Ltd, https://www.stwater.co.uk/developers/

1.2 Aims and Objectives

This work came about as a result of the 2010-2012 drought which highlighted the continued vulnerability of water resources to drought and the need for continued drought research in the UK. It was the most significant drought across England and Wales since 1995-96; which is often considered a benchmark drought alongside 1975-76, 1933-35 and 1921-23. The 2010-12 drought prompted a re-evaluation of drought risk and water resource management plans across the UK. It also highlighted a lack on long-term knowledge and understanding of drought in the UK, with several water companies concerned about provision capability, with estimates of drought frequency and severity determined on short and often incomplete data series, with poor understanding of how drought could manifest across different drought types (see Section 1.1). As a result of these unknowns, this work was funded by a Natural Environment Research Council (NERC) CASE studentship [NE/J50015X/1] in partnership with Severn Trent Water to investigate how drought and its implications for water resources the Severn Trent region; as part of this studentship six months were spent working within the water resource strategy team at Severn Trent Water Ltd in Coventry. The aim of this thesis is *"An Investigation of Drought in the Severn Trent Water Region: Re-evaluating drought severity, characteristics and generating mechanisms",* this will be achieved through five objectives, which are:

i. reconstruct and examine historic meteorological droughts using the Standardised Precipitation Index (SPI) from 1858 onwards, and to apply a drought reconstruction in a water resources yield assessment to evaluate historic drought severity.
ii. investigate the spatial and temporal coherence of meteorological drought using 15 sites across the Severn Trent Region to examine drought variability and how this would impact water resources management.
iii. examine the propagation of meteorological drought into the terrestrial component of the hydrological cycle and water resource system using a drought index approach to examine hydro(geo)logical drought responses using streamflow, reservoir and groundwater data.
iv. explore drought structure at the catchment scale by coupling meteorological and hydro(geo)logical datasets to better understand the relationship between these drought types.
v. to examine links between the atmospheric circulation indices; (1) Atlantic Multidecadal Oscillation, (2) North Atlantic Oscillation and (3) East Atlantic-West Russia and the SPI to better understand the potential of the SPI and these atmospheric circulation indices for drought monitoring.

1.3 Thesis Outline

This thesis is split into eight chapters. Chapter 1 provides an introduction, presents the principle aims and the thesis outline. The literature review (Chapter 2) will present the major themes in the state of the art of drought research that is relevant to this thesis. Chapter 3 provides details on the study area, data and methods. Chapter 4 presents the reconstruction of historical meteorological droughts and the application of a drought reconstruction for a water resource yield assessment and investigates the spatial and temporal variability of drought in the study region. Chapter 5 examines the hydroclimatology of individual drought events, to gain a better understanding of drought propagation, drought structure and drought generating mechanisms. The discussion (Chapter 6), assesses how the principle aims have been addressed, whilst the implications of this research for water resource management are presented in Chapter 7. Finally, Chapter 8 presents the conclusions.

Within this thesis there are embedded previously published papers therefore some repetition will occur.

1.4 Status of Manuscripts

Chapter 4: Lennard, A.T., Macdonald, N., Hooke, J., 2014. Analysis of drought characteristics for improved understanding of a water resource system, in: Castellarin, A., Ceola, S., Toth, E., Montanari, A. (Eds.), *Evolving Water Resources Systems: Understanding, Predicting and Managing Water–Society Interactions Proceedings of ICWRS2014,* Bologna, Italy, June 2014 (IAHS Publ. 364, 2014). IAHS, pp. 404–409. doi:10.5194/piahs-364-404-2014 404)

Author contribution:

Lennard, A.T. — Main author responsible for data collation, data processing, statistical analysis, figures and tables and manuscript preparation.

Macdonald, N. — In depth discussion and detailed manuscript review.

Hooke, J. — In depth discussion and manuscript review.

Chapter 4: Lennard A.T., Macdonald N. Clark S. & Hooke J.M., 2016. The application of drought reconstruction in water resource management, *Hydrology Research*, 7(3):646-659, doi: 10.2166/nh.2015.090)

Author contribution:

Lennard, A.T. — Main author responsible for data collation, data processing, statistical analysis, figures and tables and manuscript preparation.

Macdonald, N. — In depth discussion and detailed manuscript review.

Clarke, S. — In depth discussion and detailed manuscript review.

Hooke, J. — In depth discussion and manuscript review.

Chapter 2

Literature Review

This chapter will present the major themes in the state of the art of drought research that is relevant to this thesis.

As discussed in Chapter 1, there is clear need for continued drought research. This chapter presents a focused review of drought research literature that frames the work detailed in this thesis. The concept of drought has been discussed and reviewed extensively by Yevjevich (1967); Dracup et al. (1980); Wilhite and Glantz (1985); Panu and Sharma (2002); Mishra and Singh (2010) and Sheffield and Wood (2011). As a full review is beyond the scope of this thesis, this literature review is focused on major themes that are key in this thesis:

1) Quantification of drought using indices
2) Drought propagation
3) UK drought research with a focus on intra-regional variability and the reconstruction of historic droughts
4) Drought management

2.1 Identifying, Quantifying and Characterising Drought

The identification, quantification and characterisation of drought is critical to better understand drought processes and impacts, however, the complexity of drought over space and time and the multifaceted nature of their impacts presents a challenge. To quantitatively characterise (onset, severity, duration and termination) drought several analysis tools have been devised. In general, drought is analysed using time-series data from a variable of interest (e.g. precipitation or streamflow) on timescales that vary from days, months to years (Mishra and Singh, 2010). Typically, these variables are then analysed in one of two ways; (1) a threshold-level approach that is derived from the theory of runs concept (Yevjevich, 1967; Dracup et al., 1980; Hisdal et al., 2004; Fleig et al., 2006); or, (2) drought indices (Palmer, 1965; Shafer and Dezman, 1982; McKee et al., 1993; Shukla and Wood, 2008).

2.1.1 Threshold-level Method

The threshold-level method of drought identification defines severity *S*, which is the product of duration *D*, for the length of time the selected variable (e.g. precipitation) is below a truncation threshold and magnitude (or intensity) *M*, the average departure from the threshold level for the duration of the event (Keyantash and Dracup, 2002). The threshold level is determined by the type of water deficit under investigation, for example a value relating to a specific water-use demand or a value that represents low flow conditions defined by percentiles (e.g. $Q_{70,}$ a flow that is equal or exceeded 70 per cent of the time) (Fleig et al., 2006). The chosen threshold level can either be fixed or variable (e.g. seasonally or monthly) taking seasonal variability into account (Hisdal et al., 2004). A drought event occurs when the variable of interest is below the defined threshold. Severity can be defined by the drought deficit volume, which has physical meaning and is a key strength of this approach (Wanders et al., 2010).

The threshold-level method can be used for all drought types (meteorological, agricultural, hydrological and groundwater) and allows for the comparison of drought state between variables, which in turn enables the examination of drought propagation (Van Loon, 2013). There are numerous examples of the application of this method in the literature, including Hisdal et al. (2001), Paulo and Pereira, (2009), Van Loon and Van Lanen (2012), Wong et al. (2013) and Sung and Chung, (2014).

2.1.2 Drought Indicators

Drought indicators (or drought indices) are a commonly used approach to identify, quantify and characterise drought events. Numerous drought indices have been developed to quantify drought for each classification (section 1.1) and have been extensively reviewed (Heim, 2002; Keyantash and Dracup, 2002; Mishra and Singh, 2010; Sheffield and Wood, 2011; Dai, 2011). The most commonly used drought indices include the Palmer Drought Severity Index (PDSI) (Palmer, 1965), Standardised Precipitation Index (SPI) (McKee et al., 1993), and most recently the Standardised Precipitation Evaporation Index (SPEI) (Vicente-Serrano et al., 2010). Other drought indices include Surface Water Supply Index (Shafer and Dezman, 1982), Reconnaissance Drought Index (Tsakiris et al., 2007), Crop Moisture Index (Palmer, 1968) and Standardised Runoff Index (Shukla and Wood, 2008).

Key features of drought indicators include the ability to quantify drought at various time-scales (Mishra and Singh, 2010) and compare drought severity at a number of locations regardless of local climate (Vicente-Serrano et al., 2012). Friedman (1957, cited in Heim, 2000) states that a drought index should meet four requirements; (1) the timescale should be appropriate to the moment in hand; (2) the index should be a quantitative measure of large-scale, long-continuing drought conditions; (3) the index should be applicable to the problem being studied; (4) a long accurate past record of the index should be available or computed. The following sub-sections in section 2.2 present an overview of the most commonly used drought indicators and the most recent developments in the formulation of drought indicators that have informed the work presented in this thesis.

2.1.3 Meteorological Drought Indicators

The Palmer Drought Severity Index (PDSI) (Palmer, 1965) is considered the first comprehensive method to assess regional moisture state (Mishra and Singh, 2010). The PDSI uses a two-layer bucket-type water balance model based on data for precipitation, temperature and available water content of the soil to estimate moisture supply (precipitation) and demand (potential evapotranspiration). The index is based upon a set of empirical relationships to quantify moisture supply standardised in relation to local climatological norms. The main advantage of the PDSI is its standardised nature, which allows for the comparison of drought state over space and time (Lloyd-Hughes and Saunders, 2002). Whilst the original PDSI methodology was formulated for use in the USA it has been applied across the globe (Jones et al., 1996; Lloyd-Hughes and Saunders, 2002; Zhai et al., 2010; Sheffield et al., 2012; Haslinger et al., 2014).

Although the PDSI has been extensively used there are a number of assumptions and limitations discussed by Alley (1984), McKee et al. (1995), Heim (2002), Keyantash and Dracup (2002) and Mishra and Singh (2010). The main limitations and assumptions include; (1) specified timescale is more appropriate for monitoring agricultural drought than that of longer timescales e.g. hydrological drought (Hayes et al., 1999); (2) the underestimation of run-off, it is assumed that run-off generation only occurs after the soil layers are saturated (Hayes et al., 1999); (3) assumption that all precipitation falls as rain may result in questionable results in winter and at high elevations (Mishra and Singh, 2010); and, (4) empirical constants derived for climatic characteristic and duration factors that influence spatial comparability of the PDSI were calculated using values from nine US climate stations

(Lloyd-Hughes & Saunders, 2002); these values are used in all PDSI calculations regardless of the climate of the study site. The self-calibrated PDSI (scPDSI) devised by Wells et al. (2004) presents a progression of the original methodology that allows for improved global application. The scPDSI is widely used in the literature (Briffa et al., 2009; Dubrovsky et al., 2009; Todd et al., 2013). However, the scPDSI does not fully address the limitations of the PDSI, namely its fixed temporal scale (between 9- and 12-months), this lack of flexibility restricts its use in the identification of different drought types (Ionita and Chelcea, 2015).

Standardised Precipitation Index (SPI)

The Standardised Precipitation Index (SPI) (McKee et al., 1993) is one of the most commonly used meteorological drought indicators. The SPI is based on the transformation of time-series rainfall data into a normal distribution, with a mean of zero and standard deviation of one. Briefly, the SPI methodology involves fitting an appropriate cumulative probability distribution function to precipitation data, which can then be transformed into a normal distribution. The SPI quantifies and characterises both wet and dry conditions at multiple timescales / accumulation periods, typically between 1- and 24-months. These timescales are designed to reflect various usable water sources, soil moisture at shorter timescales (1-3 months) and streamflow, groundwater, lakes and reservoirs at longer timescales (3 – 24 months) (Szalai and Szinell, 2000). The index is dimensionless, with values typically ranging between 3 and -3, with negative values indicating drought conditions and positive values indicating wet conditions; each SPI category has an associated probability based on the fitted distribution (Table 2.1).

Table 2.1: SPI classifications and associated probabilities

SPI Value	Classification	Probability
2.00 or more	Extremely Wet	2.3%
1.50 to 1.99	Severely Wet	4.4%
1.00 to 1.49	Moderately Wet	9.2%
0.99 to -0.99	Near Normal	68.2%
-1.00 to -1.49	Moderate Drought	9.2%
-1.50 to -1.99	Severe Drought	4.4%
-2.00 or less	Extreme Drought	2.3%

Use of the SPI is abundant in scientific literature at global (Farahmand et al., 2015), regional (e.g. pan-European) (Spinoni et al., 2015) and local scales (i.e. national or sub-national) (Costa, 2011). Such is the success of the SPI, it is the recommended meteorological drought indicator by the World Meteorological Organisation (WMO) for national meteorological and hydrological monitoring services (WMO, 2012). Key strengths of the SPI include- (1) multi-scalar nature- allowing computations at multiple timescales; (2) simplicity- only requiring precipitation data; and, (3) standardised approach allows for consistent comparison of drought state at any timescale and location (Hayes et al., 1999). However, there are limitations to the SPI, these include- (1) the standardised nature of the SPI does not allow for the identification of 'drought-prone' regions, as droughts are assumed to occur with the same frequency at all locations; (2) there is an assumption that a suitable probability distribution can be fitted to the precipitation data; (3) SPI requires at least 30 years of precipitation data (Hayes et al., 1999); and, (4) the influence of multidecadal climate variability is not taken into account (Núñez et al., 2014). The second and third limitations listed above are the subject of numerous studies.

SPI computation methods and requirements have been extensively tested, including Guttman (1994), Guttman, (1999), Wu et al. (2005), Sienz et al. (2012) and Stagge et al. (2015b). Ideally, the SPI should be calculated using long-term rainfall data of at least 30 years (McKee et al., 1993). However, Guttman (1994) suggests when fitting probability distributions that at least 40-60 years of data are required to obtain stable parameter estimations in the central portion of a distribution and 70-80 is needed for stable estimates in the tails of the data. Wu et al. (2005) investigate the impact of rainfall data record length on SPI result, concluding that differences in SPI values calculated using different lengths of rainfall record are small provided the parameters (shape and scale) identified by distribution fitting are similar. Wu et al. (2005) also conclude that SPI results are more reliable when longer rainfall records are used, as they are more likely to capture climate variability signals.

In the original SPI methodology, McKee et al. (1993) suggest that the two-parameter gamma distribution function should be used to "define the relationship of probability to precipitation" (pp. 18). Although the gamma distribution is extensively used (Lloyd-Hughes and Saunders, 2002; Mishra and Singh, 2009; Dubrovsky et al., 2009; Haslinger et al., 2014; Kingston et al., 2015) various alternative distributions are also proposed, for example, Pearson Type-III (PE3) used by Guttman (1999), Vicente-Serrano (2004), Dogan (2012), Poison-gamma by Lana et al. (2001), log-normal by Touma et al. (2015) and the Tweedie distribution (Barker et al., 2016). The selection of an appropriate probability distribution is critical to avoid bias towards wetness or dryness in SPI values (Sienz et al., 2012).

In an examination of the suitability of the gamma distribution. Sienz et al. (2012) compare it with Weibull, Burr Type III, exponentiated Weibull and generalised gamma distributions. These distributions were tested using multiple precipitation datasets including the England and Wales precipitation series (one of the longest records in the world, starting in 1766), a gridded global land area series and a simulated rainfall series based from a coupled atmosphere-ocean model. Sienz et al. (2012) conclude that the gamma distribution cannot adequately represent precipitation for considerable regions of the globe based on both observed and simulated datasets. They suggest that a multiple distribution approach based on the best-fit distribution for each month and location is preferential. However, when spatial and temporal comparability are important, a single best-fit distribution is suggested (Sienz et al., 2012). A multi-distribution approach is problematic as the sensitivity in the tails of the SPI data could result in inconsistencies between different datasets with varying distributional qualities (Farahmand and AghaKouchak, 2015).

Stagge et al. (2015) investigate the best fit theoretical distributions for SPI at various accumulation periods using gridded rainfall data for Europe; probability distributions tested are gamma, Gumbel, Weibull, log-logistic, normal, logistic and lognormal. Findings show that there are a number of distributions that best fit rainfall accumulation periods across Europe. Broadly, the results indicate that at the shortest SPI accumulation period (1-month) the Gumbel distribution is the dominant best fit. At longer accumulation periods (3-months or more) lognormal, normal and gamma are the dominant best fit distributions in temperate climates. Across Europe the gamma distribution is the only one able to produce a relative good fit, therefore, Stagge et al. (2015) suggest that the gamma distribution should be used for regional studies within Europe.

Standardised Precipitation Evaporation Index (SPEI)

Developed by Vicente-Serrano et al. (2010) the standardised precipitation evaporation index (SPEI) builds on the SPI in that it considers the role of evapotranspiration (ET) in the formation of drought. This is particularly important in semi-arid and arid climates (e.g.

Mediterranean climates) and in the role of temperature in drought formation, which is particularly useful for the study of climate change impacts on drought (Beguería et al., 2014). The SPEI combines the simplicity of the SPI with the consideration of evaporative demand included in the PDSI (Vicente-Serrano et al., 2012).

The SPEI uses a similar computational approach to the SPI, but requires both precipitation (P) and potential evapotranspiration (PET) data to calculate a climatic water balance (D) (D = P - PET) which is then used to compute the SPEI. The original SPEI methodology suggests the use of the Thornthwaite (1948) PET equation (Vicente-Serrano et al., 2010), which represents one of the simplest methods for the calculation of PET, requiring only mean-monthly temperature and latitude of the site under investigation.

Like the SPI, the SPEI is multi-scalar and uses the same drought classifications set out in Table 2.1. A key difference between the SPI and SPEI is the theoretical probability distribution used to fit the climatic water balance data. The SPEI requires a three-parameter univariate distribution, whereas the SPI typically uses a two-parameter distribution (Vicente-Serrano et al., 2010). A two-parameter distribution is bounded at zero and does not permit negative values, whereas three-parameter distributions have a location parameter allowing negative values which are present in a climatic water balance (Stagge et al., 2015). In the original computation of the SPEI Vicente-Serrano et al. (2010) recommend the log-logistic distribution based on the testing of a number of three parameter distributions including Pearson Type III, log-normal and generalised extreme value.

As the SPEI is a relatively new drought index there has been little testing to assess its methods and assumptions; those who have tested this index include Beguería et al. (2014), Stagge et al. (2014) and Stagge et al. (2015). Beguería et al. (2014) present methodological progressions of the original SPEI computation, including greater flexibility in the calculation of evapotranspiration and alternative methods in distribution fitting. Whilst PET using the Thornthwaite equation is suggested in the original SPEI methodology (Vicente-Serrano et al., 2010), Beguería et al. (2014) suggest that the Penman-Monteith reference evapotranspiration (ET_0) is the preferred ET calculation method. Stagge et al. (2014) investigate the sensitivity of the SPEI to various ET calculation methods, suggesting that the Hargreaves and Penman-Monteith ET_0 methods are preferable to the Thornthwaite equation. Stagge et al. (2015) test the findings of Vicente-Serrano et al. (2010) that the log-logistic distribution is the most suitable to normalise SPEI results. A number of univariate distributions (generalised logistic, generalised extreme value (GEV), normal and Pearson Type III) are tested at multiple timescales (1-, 2-, 3-, 6-, 9- and 12-months); results show that the GEV distribution consistently provides the best fit across all timescales. Stagge et al. (2015) suggest that the GEV distribution should be used in the computation of the SPEI for regional studies in Europe.

Despite a lack of interrogation of the methods and assumptions, since its development, the SPEI has been extensively used in the literature for various applications in drought research. Vicente-Serrano et al. (2011) investigate the link between SPEI and El Nino-Southern Oscillation (ENSO) at the global scale. McEvoy et al. (2012) examine the suitability of the SPI and SPEI for the monitoring of hydrological drought throughout Nevada and eastern California; concluding that the SPEI is a preferred monitoring indicator in this location. Hernandez et al. (2013) assess future drought occurrence in coastal Texas using the SPEI with temperature and precipitation data from a downscaled global circulation model. Haslinger et al. (2014) examine the relationship between the SPEI and hydrological drought across Austria. Spinoni et al. (2015) assess European drought climatologies from 1950 to 2012, using various meteorological drought indices including the SPEI. Liu et al. (2016) analyse the spatio-temporal characteristics of meteorological drought across the Loess Plateau, China using the SPEI.

2.1.4 Hydro(geo)logical Drought Indicators

Whilst multi-scalar meteorological drought indices such as the SPI and SPEI can be computed at time-steps that are considered representative of hydro(geo)logical drought, only analysis of surface and groundwater variables can appropriately quantify and characterise hydro(geo)logical droughts. For example, Teuling et al. (2013) find that the use of hydrological drought indices provides greater insight into hydrological drought severity and spatio-temporal evolution that cannot be identified, when compared to using meteorological drought indicators alone. Van Loon et al. (2014) find that in regions with strong seasonality, the non-linear nature of drought response between meteorological state and soil moisture, streamflow and groundwater states means that characterisation of hydrological droughts from meteorological indicators is not straightforward.

Hydrological drought indicators appear to be used less frequently than meteorological drought indicators in the drought literature; the threshold-level method is typically used in the analysis of hydrological drought (Vicente-Serrano et al., 2012). The most established hydrological indices are the Palmer Hydrologic Drought Index (PHDI) (Palmer, 1968) and the Surface Water Supply Index (SWSI) (Shafer and Dezman, 1982). More recently, other hydrological drought and groundwater drought indicators have been developed including the Standardised Runoff Index (SRI) (Shukla and Wood, 2008), Streamflow Drought Index (SDI) (Nabaltis and Tsakiris, 2009), Standardised Streamflow Index (SSI) (Vicente-Serrano et al., 2012) and the Standardised Groundwater Index (Bloomfield and Marchant, 2013).

Palmer Hydrologic Drought Index (PHDI)

The PHDI, developed by Palmer (1968), originates from the PDSI and is designed to determine the long-term impact of drought on hydrological systems. The key difference between the PDSI and PHDI is the drought termination criterion; the PDSI has an abrupt return to near normal conditions, whereas the PDHI has a more gradual event termination (Karl et al., 1987). Based on the PDSI a drought is considered to have ended in the first month of a series of months with sufficient moisture to terminate a drought, whereas the PDHI considers a drought to be terminated in the last month of a series of months with sufficient moisture to terminate a drought (Karl et al., 1987). This change in drought termination criterion is designed to reflect the lag in drought recovery between the termination of a meteorological drought and hydrological drought (Vicente-Serrano et al., 2012).

Surface Water Supply Index (SWSI)

The Surface Water Supply index (SWSI) (Shafer and Dezman, 1982) is formulated to assess surface water availability by incorporating snowpack, streamflow, reservoir storage and precipitation into a single number for an entire catchment. The original calculation is designed to complement the PDSI (using a similar scale) in mountainous, high altitude regions of Colorado (Heim et al., 2002). A key concept in the SWSI is the use of non-exceedance probabilities to normalise the index, allowing the comparison of drought state between catchments in different regions (Garen, 1993). The SWSI is an operational drought index that is incorporated into drought monitoring across the western USA (Doesken et al., 1991); however, despite this uptake there are issues with the SWSI. Key criticisms include: (1) computation of various SWSIs which do not share the same statistical behaviour, suggesting that results between catchments are not comparable (Doesken et al., 1991) and (2) the combination of multiple hydrological variables into a single index value can mask the true resource state where one source can compensate for another (Garren, 1993).

Standardised Runoff Index (SRI)

More recently developed hydrological drought indicators and groundwater drought indicators are designed to reflect the broad appeal and apparent simplicity of the SPI; this contrasts with both PDHI and SWSI which are computationally intensive and have substantial data requirements. The Standardised Runoff Index (SRI), devised by Shukla and Wood (2008), applies the SPI concept to modelled streamflow data- a probability distribution is fitted to streamflow data at various accumulation periods (e.g. 1-, 3- and 12-months) and transformed into a normal distribution. Shukla and Wood (2008) use the two-parameter log-normal probability distribution, but also state that the three-parameter log-normal and the generalised extreme value distributions may all be applicable. However, the fitting of probability distributions to the accumulated streamflow data is problematic; auto-correlation in the overlapping accumulation periods can create bias in distribution fitting (Kao et al., 2014).

Streamflow Drought Index (SDI)

The Streamflow Drought Index (SDI), developed by Nabaltis and Tsakiris (2009), is also based on the SPI concept, but uses observed streamflow to analyse hydrological droughts. Like the SRI, the SDI also proposes the use of data accumulated over multiple months, but the SDI focuses on characterising hydrological droughts at a seasonal timescale within a hydrological year, resulting in accumulation periods of 3-, 6-, 9- and 12-months (e.g. October-December, October-March) (Nabaltis and Tsakiris, 2009). The SDI like the SRI uses the two-parameter log-normal distribution to fit the accumulated streamflow data before transformation to a normal distribution. In an assessment of the SDI for the monitoring of hydrological droughts in Iran Tabari et al. (2013) find that the two-parameter log-normal distribution provides the most suitable fit at all accumulation periods.

Standardised Streamflow Index (SSI)

Vicente-Serrano et al. (2012) test the suitability of the log-normal distribution, used in the both the SRI and SDI, in the computation of the Standardised Streamflow Index (SSI). Testing multiple probability distributions is a useful step in the acceptance of a hydrological drought indicator methodology. Streamflow typically has greater spatial variability than climatic variables attributable to factors including catchment characteristics and anthropogenic influences; consequently, there is greater variation in best fit probability distributions in streamflow data (Vicente-Serrano et al., 2012). Six three-parameter probability distributions (generalised Pareto, Pearson Type III, log-logistic, log-normal, generalised extreme value and Weibull) are used to test whether- (1) a single probability distribution can fit all monthly flows recorded at a gauging station, and (2) if different probability distributions are required to fit each monthly series recorded at a gauging station. Key findings include the variability in best-fit distributions between months and streamflow gauges, suggesting that it is not feasible to have a single distribution suitable for all months and all gauges (Vicente-Serrano et al., 2012). In the computation of the SSI Vicente-Serrano et al. (2012) advocate the use of a different probability distribution for each gauging station and month if necessary; this approach is also used by López-Moreno et al. (2013). If a single distribution is used for all sites and all months, either the generalised extreme value or log-logistic is recommended.

Standardised Groundwater Index (SGI)

Of all climatological and hydro(geo)logical variables analysed in drought research, groundwater appears to be the most overlooked; in comparison to hydrological drought indicators there are a few groundwater drought indicators. The most recently developed groundwater drought indicator is the standardised groundwater index (SGI), devised by Bloomfield and Marchant (2013). Like the SRI, SDI and SSI, the SGI is also based on the SPI; however, the key difference between those indicators and the SGI is the removal of probability distribution fitting in its computation. In the analysis of multiple groundwater level records across the UK, Bloomfield and Marchant (2013) find that the high level of variability in fitted probability distributions and the resulting normalised values cannot be objectively compared. Their solution to this issue is the use of a non-parametric standardisation approach. A normal scores transformation is used by applying the inverse normal cumulative distribution to monthly groundwater levels. This computation approach produces normalised SGI values that will always pass the Kolmogorov-Smirnoff test for normality (Bloomfield and Marchant, 2013). The SGI is not a multi-scalar index, but calculated at a 1-month timescale, as a continuous variable it is unnecessary to accumulate groundwater data over multiple months. Bloomfield and Marchant (2013) conclude that the SGI provides a robust quantification of groundwater drought, this is tested through the correlation of the SGI and SPI (at multiple SPI timescales) and the agreement between SGI values and past documented droughts. A non-parametric approach for the computation of the SGI is also used in Kumar et al. (2016) to assess the SPI-SGI relationship for more than 2000 groundwater boreholes in Germany and the Netherlands.

2.1.5 Standardised Drought Indicators

The development of standardised hydro(geo)logical drought indicators to complement standardised meteorological drought indicators (SPI and SPEI) provides a robust method to quantify and characterise different drought types in a consistent and comparable manner. These indices, collectively referred to throughout this thesis as standardised drought indicators (SDI), have been receiving increasing attention in the literature (Núñez et al., 2014, Soláková et al., 2014; Folland et al., 2015; Farahmand and AghaKouchak, 2015).

Núñez et al. (2014) assess the use of the SSI as an extension of the SPI and the potential policy implications of its use. This work highlights limitations in the use of the SPI and SSI as a result of multidecadal climate variability. For example, any changes in the structural stability of hydrological data through time associated with multidecadal climate variability can influence probability distribution properties, which could influence the length of data analysed, contrary to the recommendation that the longest records available should be used. Núñez et al. (2014) also discuss the implications of the lack of reference periods (climate normals) in the calculation of the SPI/SSI, which is typically calculated based on entire dataset length, concluding that these limitations should be considered in the adoption of the SDI for drought management.

Despite the recent interest in SDIs as a consistent methodology to analyse drought in a range of variables, questions have been raised over the comparability of these indicators as a result of fitting various probability distributions in the computation process (Bloomfield and Marchant, 2013; Soláková et al., 2014; Farahmand and AghaKouchak, 2015). In the development of the SGI Bloomfield and Marchant (2013) propose a non-parametric, normal scores transformation computation method that aims to overcome this problem. For consistency, the SPI computed in Bloomfield and Marchant (2013) is also calculated using this non-parametric approach. The same methodology has subsequently been used in Folland et al. (2015). Soláková et al. (2014) compare SPI and SSI values computed using both parametric and non-parametric methods, finding that the key differences between the two methods is drought severity; the parametric approach results in more extreme values. Farahmand and AghaKouchak, (2015) propose a framework for computing non-parametric SDIs for precipitation, soil moisture and relative humidity. This framework uses the empirical Gringorten plotting position to derive the marginal probability of the variables of interest. Results show that the non-parametric SDIs are primarily consistent with parametric results, indicating that the non-parametric SDIs can reliably represent wet and dry phases, but there are differences in the tails of the data where the parametric SDIs may be least accurate (Farahmand and AghaKouchak, 2015). A key advantage of the non-parametric approach is the increased simplicity in computational demands by removing the need to fit probability distributions and calculate goodness-of-fit statistics. However, the parametric approach has been favoured because the specification of a probability distribution allows the extrapolation of the empirical cumulative distribution function to forecast future rainfall or streamflow (Soláková et al., 2014).

2.1.6 Multivariate Drought Indicators

Different drought types are typically analysed individually; whether using drought indices or the threshold level method, each variable of interest is examined separately (e.g. SPI and SSI). However, drought conditions are associated with multiple factors, for example, low precipitation, high temperatures and low relative humidity (Hao and Singh, 2015). In an attempt to capture this complexity, numerous multivariate drought indicators have been developed (Keyantash and Dracup, 2004; Hao and AghaKouchak, 2013; Rajsekhar et al., 2015; Ma et al., 2015). In a review of multivariate drought indicators Hao and Singh (2015) outline the recently developed indicators, with a particular focus on the methods used to combine each variable of interest. Several methods are available, including principle component analysis, joint probability distributions and linear combinations. They conclude that whilst multivariate indicators offer a progression in the characterisation of drought, they are not fundamentally superior to univariate indices. Despite the recent development of multivariate approaches, Fleig (2006) cautions that different drought types (e.g. meteorological or hydrological) may not occur simultaneously or exhibit equal severities, therefore they should be characterised separately.

2.1.7 Overview

In providing an overview of drought indicators, section 2.1 highlights the range of indices available to quantify and characterise droughts and the importance of selecting the most appropriate indicator for the work being undertaken. Whilst section 2.1 has focused on the computation of these indices, examples of their use can be found across the literature for a wide range of drought related problems, at a range of scales. For example, Kingston et al.

(2015) assess the linkages between the SPI/SPEI and atmospheric circulation drivers of meteorological across Europe. On a smaller scale, Bloomfield et al. (2015) use the SGI to regionalise groundwater droughts in the east of England. The varied use of drought indicators in the literature shows their value in the field. However, they are not without their limitations and a single indicator is not sufficient to reflect the complexity of a drought therefore, the use of multiple indicators that can be consistently compared is vital for appropriate drought monitoring (Botterill and Hayes, 2012). Further issues related to the use of drought indicators for drought management are presented in section 2.4.

2.2 Drought Propagation

The development of a drought from a meteorological phenomenon into the terrestrial component of the water cycle (into agricultural, hydrological and groundwater droughts) can be described as drought propagation; a term coined by Eltahir and Yeh (1999). Briefly, this process can be described as a deficit in precipitation and/or increased evapotranspiration resulting in decreased soil moisture content, which causes a reduction in surface run-off and groundwater recharge that in turn reduces streamflow levels and groundwater levels. However, in reality the propagation of drought is far more complex resulting from processes including feedbacks with vegetation, the interaction between surface water and groundwater, catchment characteristics and the role of climate control (Wang et al., 2016). The general characteristics of drought propagation can be summarised in four key terms (Van Loon and Van Lanen, 2012); (1) *pooling*- multiple meteorological droughts are combined into a sustained hydrological drought, (2) *attenuation*- meteorological droughts are attenuated in stores (e.g. surface waters), (3) *lag*- the lag that occurs between each drought type, and (4) *lengthening*- increased duration of droughts moving from meteorological to soil moisture to hydrological and groundwater droughts. These four characteristics are regulated by catchment (lag and attenuation) and climate controls, with pooling and lengthening a function of both climate and catchment controls. An overview of the drought propagation concept and processes can be found in Van Loon (2015).

Typically, the threshold level approach is used to examine drought propagation; these include studies by Eltahir and Yeh (1999); Peters et al. (2003); Peters et al. (2005); Tallaksen (2006); Van Lanen (2006); Peters et al. (2006); Tallaksen et al. (2009); Van Loon and Van Lanen (2012); Van Loon (2013). The threshold level approach is particularly suited to propagation studies where a uniform methodology can be applied across different variables allowing for consistent comparisons. However, drought indices can also be employed in this type of study, examples include Vicente-Serrano and López-Moreno (2005); Di Domenico et al. (2010); Vidal et al. (2009); Bloomfield and Marchant (2013); Barker et al. (2016).

Climate controls are critical in the propagation of drought, Van Lanen (2006) investigates propagation processes for catchments in The Netherlands and Spain (providing contrasting climates), finding that drought in recharge tends to cluster more in drier climates. Whilst drought is typically thought of as resulting from a precipitation deficit, it is more complex, particularly when considering the role of seasonality. The role of climate in drought propagation is extensively examined to produce hydrological drought typologies in Van Loon and Van Lanen (2012). The typologies provide a common means with which to describe hydrological droughts across a broad range of catchments with different climates and their governing processes (e.g. a classical rainfall deficit drought is governed by precipitation, whereas a cold snow season drought is governed by low temperatures in cold season) (Van Loon and Van Lanen, 2012). In a global assessment of the effect of climate seasonality in the modification of drought duration and deficits, Van Loon et al. (2014) find that in climates with strong seasonality (both warm and cold climates) drought duration and deficits in soil moisture, hydrological and groundwater variables have a non-linear response to meteorological drought.

Catchment controls are also key in the propagation of drought, with Van Lanen et al. (2004) providing an overview. The most important catchment control in the development of hydrological drought is catchment storage capacity, which is governed by a variety of factors, including geology, soil type, topography, land cover, land use and drainage network (climate is also a control of catchment storage capacity in cold climates) (Van Loon, 2015). However, it is not clear which of these factors is most dominant on hydrological drought severity (Van Loon and Laaha, 2015). Investigations of both climate controls and catchment controls are undertaken by Van Lanen et al. (2013) and Van Loon and Laaha (2015). Van Loon and Laaha (2015) find that both climate and catchment controls govern drought duration and deficit, whilst Van Lanen et al. (2013) find groundwater system controls are as important as climate controls for hydrological drought development.

Groundwater responsiveness is a key factor in the development of hydrological droughts (Peters et al., 2005; Van Lanen et al., 2013). In the study of aquifer response to floods and droughts in Illinois, Eltahir and Yeh (1999) find that droughts leave a more persistent signature in groundwater levels than floods, due to the nonlinear dependence of groundwater discharge on groundwater levels. Peters et al. (2006) analyse the propagation and spatial distribution of groundwater drought in the groundwater dominated Pang catchment, UK. This study finds key differences in drought response between groundwater recharge, discharge and level; both recharge and discharge exhibit drought characteristics that can be described as frequent short events, whilst droughts are less frequent but more severe in groundwater levels (Peters et al., 2006). Tallaksen et al. (2006) also investigate drought propagation in the Pang catchment, highlighting the importance of catchment control in the modification of the drought signal into the terrestrial component of the hydrological cycle.

Whilst many studies analyse drought propagation using variations of threshold level, drought indices can also be used. Vidal et al. (2009) investigate propagation using standardised drought indices for precipitation, soil moisture and streamflow for droughts in 1976 and 2003. Bloomfield and Marchant (2013) investigate the propagation of drought into groundwater using a standardised drought indicator method (more details can be found in section 2.1.5). Using this approach, Bloomfield and Marchant (2013) identify the lag between meteorological and groundwater droughts based on maximum correlations between the SPI and SGI and stress the importance of considering the location specific influences on SGI time-series in the analysis of groundwater droughts. Barker et al. (2016) investigate the relationship between the SPI and SSI; the lag between meteorological and hydrological droughts is assessed using a 1-month SSI and multiple SPI accumulation periods. Barker et al. (2016) link drought propagation characteristics to climate and catchment controls, which highlight the role of average precipitation and catchment storage on hydrological drought characteristics. Whilst there is increasing knowledge on the propagation of drought, there remains the need to further understand how this knowledge can be applied in drought monitoring and early warning, particularly from a water resources perspective.

2.3 UK Focused Drought Research

To place the research conducted for this thesis into context, this section provides an overview of UK focused drought research that is relevant to this thesis. There has been a recent resurgence in UK focused drought research, most likely a result of the 2010-12 drought that affected much of England and Wales (Kendon et al., 2013); a similar resurgence is seen after the 1995-96 drought. There is strong regional scale focus to this research; Phillips and McGregor (1998) investigate meteorological drought in the south-west of England, Fowler and Kilsby (2002) focus on the Yorkshire region, Todd et al. (2013) examine historic meteorological drought in south-east England, Spraggs et al. (2015) focus on the Anglian region, and Folland et al. (2015) investigate meteorological and hydrological drought in the English Lowlands. However, there are also a number of studies at the UK scale, including Jones and Lister (1998), Jones et al. (2006), Rahiz and New (2012a), Bloomfield and Marchant (2013), Barker et al. (2016). The following subsections detail UK focused drought research that is divided into regional and national scale studies.

2.3.1 Regional Scale Drought Studies

In their investigation of drought in Devon and Cornwall (south-west England), Phillips and McGregor (1998) characterise meteorological droughts using four precipitation records from the late 1940s to 1996. Results identify intra-regional variability in drought climatology in north and south Cornwall. Analysis of the weather types associated with drought events in the study region indicate that there are two drought sub-types, differentiated by the locational centre of anti-cyclones over the UK; (1) droughts associated with the north and east location of anti-cyclones, and (2) those associated with the south-westerly anti-cyclonic centre that is associated with strengthening of the North Atlantic Oscillation (NAO) since the 1970s (Phillips and McGregor, 1998). Applying a similar analysis to Phillips and McGregor (1998), Fowler and Kilsby (2002) identify major meteorological drought events in Yorkshire from 1881 to 1998. The characterisation of these droughts reveals a high level of spatial variability in severity and duration across the Yorkshire region that can be classified into three spatial groups; (1) 'eastern', (2) 'western', and (3) 'regional'. The analysis of droughts over this time period (117 years) reveals a change in the speed of drought onset; later events examined (1992 and 1995) exhibited more rapid onsets compared to earlier events where equivalent rainfall deficits took longer to develop.

The analysis of historical meteorological droughts is also used in Todd et al. (2013), however, this study reconstructs drought events over a much longer time period, 1697-2013 (316 years) in south-east England. This study uses three of the longest rainfall records and the Central England Temperature (CET) series to compute the scPDSI for Oxford, Kew (London) and Spalding. Key findings include the identification of two drought-rich periods from 1730-60 and 1890-present and that the most severe and longest duration droughts identified both occur in the twentieth century; 1943-1950 and 1970-1978. This work identifies that whilst the majority of droughts are regionally coherent, there is intra-regional variability particularly in event onset and termination; droughts that are not regionally coherent are also identified (Todd et al., 2013). Spraggs et al. (2015) also reconstruct historic droughts utilising long-series climate data; this study focuses on hydrological droughts in the Anglian Region from 1798-2010. Analysis of hydrological drought characteristics reveals clusters of major winter streamflow deficits in the 1850s, 1860s, 1890s and 1900s. This regional scale study also identifies that drought coherence across the Anglian region is tempered by intra-regional variability in drought severity (Spraggs et al., 2015). By taking a regional scale approach the studies discussed above highlight intra-regional variability of meteorological and hydrological droughts across England. The study of droughts at this scale may be particularly useful in water resource assessments where sub-regional variation in drought impacts may have implications for drought management.

Other regional scale studies focus on other aspects of drought characteristics. For example, Folland et al. (2015) examine the characteristics of multi-year droughts, with a focus on the winter half-year, and their generating mechanisms in the English Lowlands, an area encompassing the south-east, East Anglia and the Midlands. This study assesses the links between the drought (SPI, SSI and SGI) and potential climatic drivers. Findings indicate links between winter rainfall deficits and La Nina phases of the El-Nino Southern-Oscillation (ENSO) for six droughts between 1910 and 2012 (1933-34, 1943-44, 1975-76, 1988-89, 1995-96 and 2010-12) (Folland et al., 2015).

2.3.2 UK Scale Studies

At the UK scale, there are a number of meteorological and hydrological drought studies. In a reconstruction of streamflow at 15 catchments across England and Wales from 1865 to 1996 Jones and Lister (1998) identify a number of major, spatially extensive hydrological droughts, notably 1870, 1887, 1921, 1933/4 and 1976. Across England and Wales, hydrological droughts tend to have shorter durations in catchments in the north and the west with longer duration events in the south and east, where groundwater is a significant component (Jones and Lister, 1998). In an update to this study, Jones et al. (2002) highlight the severity of the 1887-88 drought; 1887 represents the lowest annual streamflow totals over the 137-year analysis for three catchments, the Wharfe and the Derwent in north of England and the Teifi in south-west Wales. Droughts of the mid and late 19th century account for the lowest annual streamflow totals in six of 15 catchments examined; this highlights the importance of better understanding these historic droughts and the potential implications for their inclusion in water resource management assessments.

Whilst regional scale drought studies (Phillips and McGregor, 1998; Fowler and Kilsby, 2002; Todd et al., 2013; Spraggs et al., 2015) identify drought variability at a regional scale, Rahiz and New (2012a) examine the coherence of meteorological droughts across the UK. Findings of this study indicate that meteorological droughts are more spatially coherent across the UK between October and March and for moderate and short duration droughts; between April and September, and for longer duration and extreme events, there is less spatial coherence. It is suggested that greater spatial coherence of droughts between October and March is linked to large scale circulation anomalies such as the NAO, which has a greater effect on UK weather during winter months (Rahiz and New, 2012a). In an investigation into the persistence of meteorological and hydrological droughts across the UK, Wilby et al. (2015) find a broadly south-east to north-west gradient in the duration of hydrological droughts across the UK, with the longest drought observed in the Wensum, Norfolk at 13 seasons. However, an exception to this gradient is the Derwent catchment, Derbyshire, with a maximum observed duration of 10 seasons.

Whilst the SPI is a commonly used drought indicator and the SPEI is being used increasingly frequently, neither the SPI nor SPEI have been extensively used in the UK. Although its use is steadily growing, the most recent examples of the SPI use include Bloomfield and Marchant, (2013); Lennard et al. (2014); Lennard et al. (2015); Folland et al. (2015); Barker et al. (2016). More commonly used in the UK is the Drought Severity Index (DSI), developed by Bryant et al. (1992); it is used in Phillips and McGregor (1998), Fowler and Kilsby (2002), Rahiz and New (2012a), Rahiz and New (2012b) and Spraggs et al. (2015). An example of the use of the SPI and SSI in the UK is by Barker et al. (2016) who assess the spatial variability of drought characteristics and drought propagation behaviour across the UK. This work finds little spatial variability in meteorological drought duration and severity, but much greater spatial variability in hydrological drought characteristics. Hydrological drought variability can be broadly described as shorter, more frequent and less severe droughts in the north and the west and longer, less frequent, more severe droughts in the south and east; this variability reflects the hydrological characteristics of the south and east (Barker et al., 2016).

2.4 Drought Management and Water Resource Planning

Drought management is primarily concerned with the mitigation of drought impacts, through the development of suitable monitoring and early warning systems and risk-based drought management plans. Traditionally, the impacts of drought have been managed using a crisis management approach. Crisis management is characterised by interventions that aim to mitigate the impacts of drought during and after the event, without the development of pre-prepared plans. Although crisis management is the most commonly used response, it is considered an ineffective approach for managing drought impacts (Wilhite et al., 2005). Risk management offers a pro-active alternative approach that has been increasingly advocated across environmental policy making (Rossi and Cancelliere, 2013; Mauelshagen et al., 2014). Risk management uses planning and preparedness approaches that aim to mitigate or minimise drought impacts before, during and after droughts (Fu et al., 2013).

The risk management framework has been incorporated into the World Meteorological Organisation (WMO) and Global Water Partnership's National Drought Management Policy Guideline (GWP) (WMO and GWP, 2014). Whilst there is an increasing body of literature focused on conceptual drought management policy (Kampragou et al., 2011; Botterill and Hayes, 2012; Wilhite et al., 2014) and specific national drought management policies (Estrela and Vargas, 2012; Kiem, 2013, Marathe and Demuth, 2013) internationally there remains a lack of drought preparedness through national drought management planning and policies (Wilhite et al., 2014). Rossi and Cancelliere (2013) highlight the lack of legislation and institutional frameworks dealing with drought from a water resources management perspective in Europe.

The following sections outline drought management policy and drought management research relevant to this thesis.

2.4.1 Drought management planning and policy in the European Union

The EU Water Framework Directive (WFD) sets out a common framework for the management and planning of water resources and the protection of aquatic environments for all member states. However, a key weakness identified within the WFD is the lack of drought and water scarcity policy (Rossi, 2009). As a result, there have been a number of policy initiatives (outlined in Table 1) and EU funded research projects to improve drought management. The Drought Management Plan Report (EC, 2007) proposed the addition of supplementary Drought Management Plans (DMPs) as an optional component of the compulsory river basin management plans (RBMPs). The report details the development of DMPs at the river basin level and highlights the need for a multi-level approach that requires drought planning at the national level, river basin level and local level. A DMP should consist of three key components:

1) Indicators and thresholds for drought characterisation (onset, severity and termination)
2) Mitigation measures to reduce the impact of drought at each stage of a drought
3) Organisational/ institutional frameworks to manage droughts and to review and update DMPs.

(EC, 2007)

After the publication of the Drought Management Plan Report (EC, 2007), subsequent follow-up reports have been published to track the progress and identify key priorities of the water scarcity and drought policy initiative (CEC, 2008; CEC, 2010). These included the continued support of DMPs and the development of the European Drought Observatory (EDO) (CEC, 2007b). The EDO is a web-based service that provides data and analysis tools to provide up-to-date information on drought situations across Europe. A 2012 review of the European Water Scarcity and Drought Policy concludes that, 'whilst there has been progress in the development of DMPs their implementation has been limited' (CEC, 2012a). "A Blueprint to Safeguard Europe's Water Resources" (CEC, 2012b) identifies the priority challenges for policy makers and water managers to address in the aquatic environment, including drought. The Blueprint echoes the findings of previous EU drought policy to encourage member states to integrate drought risk management into future RBMPs. An examination of EU drought related policies indicates the need for continued implementation of drought risk management measures across EU member states. Despite the focus and progress in the development of drought risk management policy in the EU, policy gaps remain that need to be addressed (Rossi, 2009: Kampragou *et al*., 2011). Kampragou *et al.* *(*2011) identifies policy gaps in a summary of key findings of the Xerochore Project review of drought policy in the EU. Gaps identified at the EU-level include:

1) A lack of integration of between water management policy and other policy sectors, including agriculture and climate change- unexplored by scientists and policy makers.
2) Development of DMPs should be formalised within RMBPs to integrate them into the environmental objectives outlined in the WFD.
3) There needs to be greater distinction between measures for water-scarcity and drought.

(Kampragou, *et al*., 2011)

2.4.2 Drought Management in England and Wales

The following section outlines the structure of drought management policy in England and Wales. Outlining this framework in this thesis is important to provide some context to the work undertaken and its potential implications and applications within Severn Trent Water.

Drought management gained prominence during the early 1990s, in part as a result of droughts experienced between 1989-1992 and 1995-1996 and the re-structuring of the water industry. This change in structure meant the roles and responsibilities of the various bodies involved (OFWAT, Environment Agency, water companies etc.) had to be clarified. In 1997, the UK government held the Water Summit (partially in response to severe drought in 1995-96), at which it was proposed that water resource management and drought planning in England and Wales needed improvement. Following the summit water companies agreed to develop voluntary drought contingency plans. These were designed to ensure drought actions were taken during the early stages of a drought to ensure public water supplies were maintained and to balance the requirements of the public and the environment (Mawdsley et al., 2000).

Current drought management policy

Drought management planning at the water company level in England and Wales is regulated under two planning structures- water resource management plans (WRMPs) and drought plans (DPs). The Water Act 2003 introduced legislative changes that made water resource management plans and drought plans a statutory obligation for water companies. Water resource management plans set out how water companies will maintain the balance between the needs of the customer with those of the environment over a 25-year period, including during droughts and "critical periods". The term "critical period" is used to describe the point where water demand is high and water resources are low. A key component of water resource management and drought plans is the calculation of deployable output. This is defined by the Environment Agency (2011b, p. 49) as "the output for specified conditions and demands of commissioned source, group of sources or water resources system as constrained by hydrological yield, licensed quantities, environment, pumping plant/or well/aquifer properties, transfer/or output mains, treatment, water quality and levels of service." The Environment Agency water resource management plan guidelines (Environment Agency, 2012d) state that water companies should assess deployable output using data that dates from at least 1920 to capture a range of conditions including severe droughts.

The Drought Plan Regulations (2005) and the Drought Plan Direction (2011) define the legal obligations of water companies in relation to drought plans. Water company drought plans are statutory documents that detail how a company will supply water to its customers during periods of drought, whilst minimising any negative impact of its actions during a drought. They should establish the short-term operational steps a water company will take before, during and after a drought (Environment Agency, 2011b). The Environment Agency provide guidelines to help water companies prepare drought plans; they define each of the components a drought plan should include. Figure 2.1 shows a schematic diagram of each drought plan component and the links between them; components of the drought plans and the relevant descriptions are detailed in Table 2.2. These guidelines state that drought plans should consider how a company would operate in a range of drought severities, including sufficient information for the public and stakeholders about decision-making processes in the event of a drought (Environment Agency, 2011b).

Table 2.2: Policy and guidance relating to drought management at the EU level

Policy / policy initiative relating to drought	Summary
Water Framework Directive (2000)	- Protection of water bodies including mitigating the effects of floods and droughts. - Voluntary DMPs as a supplementary measure to RBMPs (Article 13.5)
Drought Management Plan Report (2007)	- Guidelines to develop voluntary Drought Management Plans, advocating the need to shift towards risk management measures.
EC communication "Addressing the challenge of water scarcity and droughts in the European Union" (2007)	- Various policy options to tackle water scarcity through pricing initiatives and improved drought risk management using drought management planning. - Development of the European Drought Observatory to create an early warning system for increased drought preparedness.
EC communication following up reports to "Addressing the challenge of water scarcity and droughts in the European Union"(2008, 2010, 2011)	- Annual follow up reports to the 2007 report to evaluate how water scarcity and drought policies were evolving across member states.
EC communication Report on the Review of the European Water Scarcity and Droughts Policy (2012)	- Concludes that overall objectives of water scarcity and drought policy have not been achieved. Identified policy gaps and future options to set out in 'Blueprint to Safeguard Europe's Water Resources'
A Blueprint to Safeguard Europe's Water Resources (2012)	- Sets out key priorities for water managers and policy makers to address challenges in the aquatic environment including droughts. - Continued development of the European Drought Observatory, encourage member states to integrate drought risk management into future RBMPs.

Drought triggers and scenarios are key components within drought plans. Drought triggers can be used to monitor drought state and have associated management actions to mitigate drought impacts. Environment Agency guidelines highlight the range of data that could be assessed to develop drought triggers to suit the needs of each water company; these include rainfall, groundwater levels, streamflow levels and reservoir levels (Environment Agency, 2011b). Drought triggers included in the most recent water company drought plans include those outlined in the Environment Agency guidelines plus soil moisture deficit, levels of demand, groundwater recharge rates and river abstraction volumes. Two drought indices (SPI and the Drought Severity Index) are included as drought triggers in one drought plan (Southern Water, 2013). Drought scenarios allow water companies to test the robustness of their water resource infrastructure to a range of drought conditions. Current drought plan guidelines suggest scenarios based on short (6-12 months), medium (1 – 2 years) and long (2 + years) duration droughts.

Water company drought plans must be consistent with other water company plans, including water resource management plans, and regulator plans such as the Environment Agency, drought plans and WFD river basin management plans (RBMPs). Prior to publication drought plans are approved by DEFRA, the Environment Agency, government ministers, and the Welsh Assembly (where required). They are also subject to a 15-week public consultation period that allows the public, interested parties and relevant stakeholders to view and comment on draft plans. After this period, final drought plans are published and publically available. The first statutory drought plans were published in 2006 and are updated every three years. Drought plans are also reviewed at the end of a drought to reflect changes that may be required based on the experience and understanding gained through the management of a drought. The 2010-2012 drought was the first major test of water company drought plans; by spring 2012 severe drought conditions were experienced across central, southern and eastern England (Kendon et al., 2013). Water companies implemented a number of the management actions outlined in their drought plans and have used knowledge gained during the 2010-12 drought to update their most recent drought plans (Thames Water, 2013; Severn Trent Water, 2014; Anglian Water, 2014).

Water company drought plans include details of possible drought orders and drought permits that may be required during a drought. Drought permits are designed to allow water companies to modify abstraction conditions placed on existing water sources and to abstract water from additional sources, if there are serious water supply deficiencies resulting from drought and temporary water use restrictions have been implemented (DEFRA, 2011). Water companies apply for drought permits through the Environment Agency. Drought orders are used when there is a serious water supply deficiency or low-flow conditions pose a serious threat to the environment. Water companies must apply for drought orders that are authorised by DEFRA or the Welsh Assembly. Drought orders allow water companies to implement non-essential water use restrictions, which allow water companies to restrict water use in commercial settings; this includes a ban on watering outdoor plants on commercial premises, parks and gardens using a hosepipe and the cleaning of vehicles, trains, aircrafts and boats with a hosepipe. Non-essential use bans have economic implications and are used when other options have been exhausted. Environmental assessments to explore the likely impacts of drought permits and drought orders must be included in water company drought plans. It is expected that water companies use mitigation measures to reduce the impacts of drought permits and drought orders on the environment (DEFRA, 2011).

Regional drought plans are developed for each of the Environment Agency regions in England and one for Natural Resources Wales, the environmental regulatory body for Wales. The plans are an operational manual for the regions to use in monitoring drought onset, impacts and drought termination (Environment Agency, 2012b). The plans include defined roles and responsibilities for designated drought teams, indicators used to classify stages of drought, drought triggers and management actions based on specific stages of the event. The Environment Agency and Natural Resources Wales work with water companies and other stakeholders to manage drought impacts on people, business and the environment (Environment Agency, 2012d). Drought triggers are based on rainfall, streamflows, reservoir levels, groundwater levels and ecological concerns, such as increased numbers of fish kills (Environment Agency, 2012d).

The Environment Agency Head Office Drought Plan (Environment Agency, 2012b) sets out how the head office drought team will plan for and manage drought events, ensuring consistency in the co-ordination of drought management at the national level, publicly report drought situations and provide advice to government on possible actions (Environment Agency, 2012b). Unlike water company drought plans, regional and national plans are not required by law; both regional and head office plans are updated every three years to co-ordinate with the updating of water company drought plans. Drought management policy in England and Wales ensures water companies manage drought risk through water resource management plans and drought plans; these are complemented by regional and national drought plans developed by the Environment Agency.

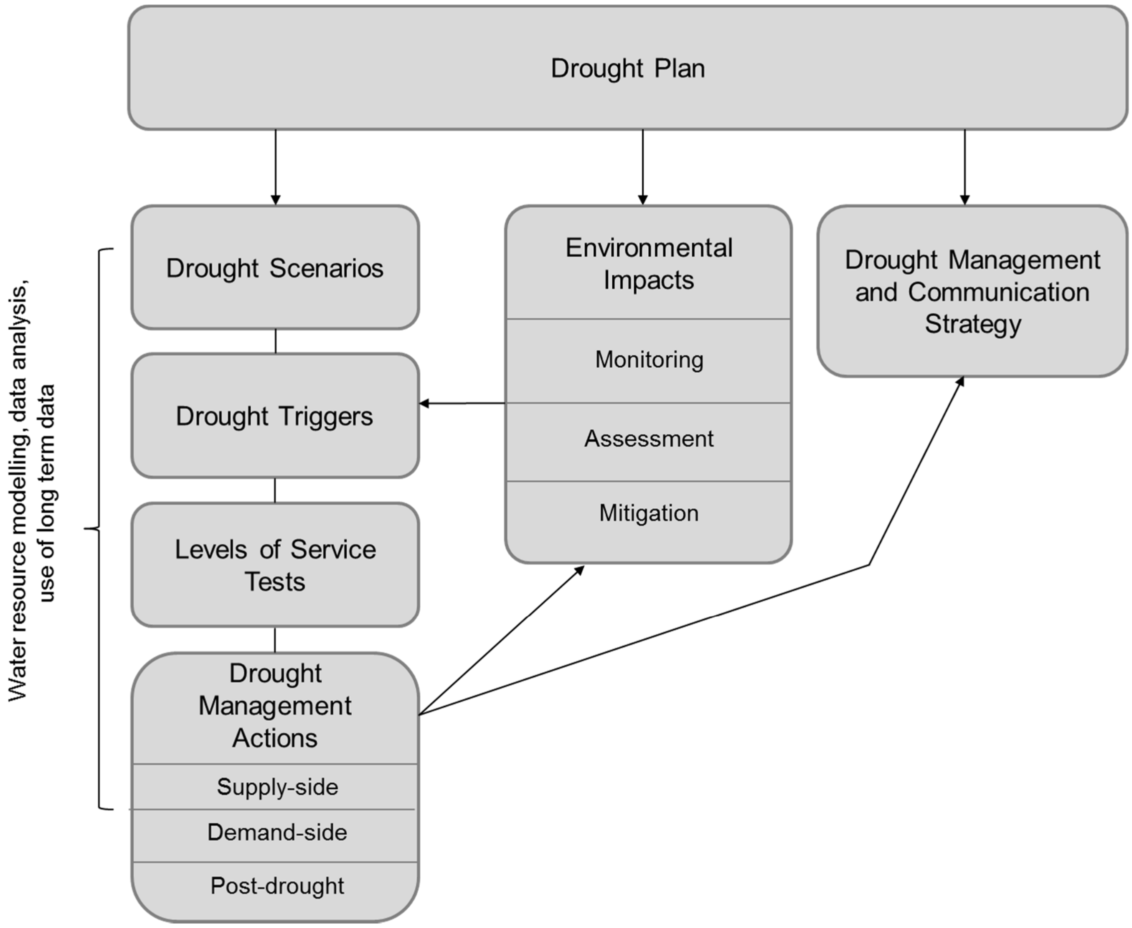

Figure 2.1: Components of a water company drought plan including the links between components

Table 2.3 Components and description of water company drought plans (based on Environment Agency, 2011)

Component	Description
Drought Triggers	Companies can identify when they should consider implementing any drought actions. They are a decision making tool within the drought management framework. There are numerous methods and data sources that can be used to define triggers e.g. historic rainfall records, reservoir levels, river flows and groundwater levels.
Drought Scenarios	Companies should assess the likely effects of past drought events if they occurred today under current water resource infrastructure, demands and operational assumptions. Water companies should test a range of scenarios appropriate to their water resource systems reflecting the variability of droughts. Different drought durations should be assessed, including: -short duration, one season droughts (typically 6 to 12 months) -medium duration, multi seasonal droughts (1 to 2 years, typically consisting of two dry summers and an intervening dry winter) -long-term drought, typically lasting over 2 years.
Drought Management Actions	Companies are required to describe management actions to reduce demand and secure additional water resources during a range of drought scenarios for each drought trigger. Management actions should be developed for demand-side and supply-side options. Post drought actions should also be developed including a review of the effectiveness of the drought plan.
Levels of Service Tests	The frequency of water use restrictions a water company expects to apply to customers.
Environmental Impacts	Supply-side drought management actions are complemented with an environmental assessment. This includes baseline monitoring when the environment is not water stressed and monitoring throughout a drought to assess the impacts of the drought and changes in supply operation. Monitoring plans and mitigation measures must also be included.
Communication Strategy	Companies should develop communication plans to publicise actions during a drought. Communication plans should increase public awareness of the development of drought conditions, reductions in water resource availability and water use efficiency.

2.4.3 Drought Management Research

In a review of drought management in water supply systems in Europe Rossi and Cancelliere (2013) promote the use of drought management plans as a risk-management tool to reduce the vulnerability of water supply systems and mitigate drought impacts. Effective drought planning requires a multi-level approach that includes various institutions and organisations; a key component of drought management planning is the management of drought risk in water supply systems. Rossi and Cancelliere (2013) identify future research challenges including increased analysis of past drought experiences in monitoring and mitigation to help define best practices in drought management, improved drought monitoring systems and improved tools and indicators that can be easily interpreted by decision makers. Planning instruments required for effective drought risk management in a water supply system include planning instruments that should:

1) Assess drought related water-shortage risk
2) Identify measures to prevent or mitigate economic and social drought impacts
3) Identify drought indicators suitable for early-warning systems and defined drought triggers linked to management actions

(Rossi and Cancelliere, 2013)

Rossi (2009) advocates that legislation at a national level should be developed to define drought management plan objectives and content, including specific drought indicators and drought declarations. Recommendations for water resource management at various levels include, defined drought scenarios with specific management actions, incorporating criteria for the implementation of emergency measures and increased public awareness through education campaigns to improve understanding of the social and economic impacts of drought (Rossi, 2009).

Use of long series climate data

The Environment Agency guidelines state that water companies should use hydrological and climate data from at least 1920 within water resource management plans and drought plans (Environment Agency, 2012c). Whilst this period captures a number of notable droughts (1921-1922, 1933-1934, 1975-1976, 1995-1996), it does not include the 'drought rich' period experienced during the late 19th Century and early 20th Century. Todd et al. (2013) reconstruct drought characteristics for south-east England using long-series climate data

(~300 years). This work identifies a number of severe droughts in the 18th and 19th Centuries that are rarely considered in water resource management. Robust assessments of drought require analysis of drought events that are outside the period of common analysis (20th Century) to understand how different drought characteristics (onset, duration, severity and termination) influence drought impacts on a water resource system. Watts et al. (2012) test the resilience of contemporary water supply systems to long droughts using scenarios based on drought events identified during the 19th Century for two reservoirs in England. These droughts were used in system modelling and an interactive workshop where water resource managers from water companies and the Environment Agency responded to emerging drought scenarios with management actions to maintain water supply throughout a drought. During the workshop management interventions were introduced that were not included in water company drought plans. Watts et al. (2012) stress the importance of effective drought management planning that allows water companies to consider a range of drought scenarios and the potential impacts on the water supply system.

Spraggs et al. (2015) reconstruct historic drought to inform water resources management planning in the Anglian region for the period 1789-2010. This is used to calculate reservoir yields under different drought scenarios. This work highlights the severity of droughts in 1854-60 and 1893-1907 attributed to a clustering of dry winters and dry summers and the value of testing water supply systems to historic droughts. Results of this work showed that pre-1920 droughts were no more severe than post-1920 droughts and reservoir yields were not reduced in the pre-1920s period. However, the utility of reconstructed long series flow data including drought conditions is useful to project a range of reservoir storage scenarios, test the robustness of current drought plans and water supply resilience to droughts beyond the current water resources modelling period (1920-2010) suggested in Environment Agency guidelines (Environment Agency, 2012d). Spraggs et al. (2015) also note the importance that further research using drought indices and long series climate data to investigate identification of drought severity, monitoring and early warning.

Drought Indicators

Drought indicators or indices are used to monitor and characterise drought conditions which typically include severity, duration and onset and termination. They are a key component of drought monitoring and early warning systems that can aid decision making water resource managers. Drought indicators are derived by analysing variables of environmental moisture e.g. precipitation, streamflow or soil moisture to determine whether drought conditions are present (Gudmundsson et al., 2014). Indices used in drought monitoring systems need to satisfy a number of requirements, such as using real-time easily available data, describing drought impact and assessing drought severity for the development of drought triggers, which can be used to activate management actions (Tokarczyk & Szalińska, 2014).

Whilst the drought indicators outlined in section 2.1 provide a valuable method to characterise and monitor drought conditions, it important to investigate their utility for operational water resource management. Vicente-Serrano and López-Moreno (2005) test the usefulness of the SPI at various timescales to monitor drought in rivers and reservoirs within a complex hydrological system in the Mediterranean. This work highlights the importance of further research to establish the relationship between drought index timescale and hydrological variables in different river basins and water resource systems.

Despite the potential use of drought indices there may be barriers to their use in an operational drought management context. Steinmann (2014) highlights the issues water managers have with ‘hard drought indicators’ (e.g. PDSI, SPI using defined numerical thresholds) in the Western United States. Water managers found drought indicators difficult to understand and interpret in relation to “drought on the ground”. In order to appropriately use drought indices for monitoring and management there is a need to link drought indices to observed socio-environmental impacts. Most drought indices can only provide a measure of meteorological or hydrological anomalies with little measure of drought impacts. In order to develop a greater understanding of the links between drought indices and drought impacts Blauhut et al. (2015) model likelihood of drought impact occurrence by exploring the relationship between the SPEI and drought impacts archived in the European Drought Impact report Inventory (EDII). Stagge et al. (2015a) link both the SPEI and the SPI with impacts in key sectors (agriculture, energy, public water supply and freshwater ecosystems) across five European countries, including the UK. Linking drought impacts with drought indices offers a method to develop predictive models of drought impacts based on the occurrence of recorded drought impacts in the EDII. This work investigated the relationship between sectoral impacts and timescale of the SPI and SPEI, concluding that public water supply in the UK requires investigation at multiple timescales from 3-month to 24-month SPI/SPEI which reflects the complex water resource picture in the UK.

2.5 Discussion

An examination of drought policy and planning guidelines in England and Wales identifies a number of drivers of drought management policy:

1) Past drought events
2) Privatisation of the water industry
3) UK legislation
4) EU directives

Current drought management policy has evolved partly in response to impacts experienced during previous droughts, particularly in the late 1980s and early 1990s. During the 1995-1996 drought 18-month rainfall totals were the third-lowest on record (1800-2002) for England and Wales (Marsh *et al.,* 2007). The resulting impacts on water resources led to water-use restrictions affecting 20 million people across England and Wales (Marsh, 1996). The first major drought since 1976, the 1995-96 drought was a challenge for the newly formed water companies and highlighted the need to improve drought management. Whilst the 1975-76 drought is often described as a 'benchmark' event it appears that the privatisation of the water industry in England and Wales resulted in the need for a more structured drought management approach in these newly regulated companies. Water company drought contingency plans were the first step towards drought risk management measures in England and Wales.

The development of the Water Resources Act 2003 and the Drought Plan Regulation 2005 advanced drought management planning in England and Wales with the inclusion of statutory consultees, stakeholder engagement and public consultation. The guidelines produced by the Environment Agency for statutory water company drought plans provide a framework to develop plans that, whilst containing key components listed in Table 2.3, allow flexibility in the methods and approaches used by each water supplier. This is reflected in the range of different drought triggers identified in water company drought plans. Although the WFD is not a primary driver of drought management in England and Wales, water company drought plans should be consistent with the WFD by consulting the relevant RBMPs to identify possible actions that could affect operations during a drought (EA, 2011b). Regional and national drought plans developed by the EA, complement the water company plans to create a multi-level approach; an approach recommended in the Drought Management Plan Report (EC, 2007).

The use of risk-management based national drought policies has been advocated by the WMO and GWP, the EU and within academic literature, but, the development of DMPs within the EU remains limited. Table 2.4 uses recommendations outlined above to develop a checklist in order to evaluate drought management England and Wales. Although drought plans are produced at multiple levels in England and Wales (water company level, Environment Agency regional levels and at the national level), there are no river basin level drought plans. This approach reflects the nature of water supply provision and regulation in England and Wales. River basin drought management plans would not necessarily be appropriate within the water supply framework in England and Wales. Several water companies operate in single river basins and also across multiple river basins, so the development of river basin DMPs would be a complex and potentially unnecessary level of drought management in England and Wales. Water companies consult with neighbouring water companies during the formation of drought plans to ensure consistency between water providers within river basins. Regional level Environment Agency drought plans may provide a comparable level in drought management to river basin drought management plans.

Table 2.4: Checklist of drought management components based on identified drought management recommendations

Identified Recommendations	**England and Wales**
DMP components (based on EC, 2007)	
Indicators and thresholds for drought characterisation	✓
Mitigation measures to reduce the impact of drought at each stage of a drought	✓
Organisational/ institutional frameworks to manage droughts and to review and update DMPs	✓
DMP levels (based on EC, 2007)	
National level	✓
River basin level	✗
Local level	✓
Drought risk-management in water supply system	
(Based on Rossi and Cancelliere, 2013)	
Assess drought related water-shortage risk	✓
Identify measures to prevent or mitigate economic and social drought impacts	✓
Identify drought indicators suitable for early-warning systems and defined drought triggers linked to management actions	✓

Investigation of the utility of the Standardised Drought Indices family

Appropriate drought mitigation requires timely management actions that are informed by early-warning and monitoring systems (Botterill and Hayes, 2012). Drought indices, such as the standardised precipitation index (SPI) and standardised precipitation evaporation index (SPEI), are valuable tools that can be used by decision makers and water managers to inform drought management actions; however, they are underutilised in England and Wales (Lennard et al., 2014). The integration of drought indices to complement drought triggers and drought management actions within drought plans could provide improved early-warning for timely decision making. Data available from past key droughts, particularly 1975-76, 1995-96 and 2010-12, could be used to investigate the links between drought indices and observed impact on stream flow, groundwater levels and water supply systems. Standardised drought indices (SDI) can be computed for multiple variables in a consistent and comparable manner that may offer a valuable monitoring and management tool in water resources management, but require further investigation including their use for examining the propagation of drought into the water resource system.

Linking drought indicators to observed drought impacts within a water supply system

Although there are a number of drought indices available, no single indicator can sufficiently characterise droughts across the broad spectrum of definitions used (Mishra and Singh, 2010); therefore, more understanding of their value is required (particularly the Standardised Drought Indicator family). It would be beneficial to link impacts to drought indicators and to understand the needs of decision makers and stakeholders. Findings of Stagge et al. (2015a) highlight the complex links between drought index and impacts on public water supply in the UK. It would be beneficial to understand these links at a water resource management level, which goes beyond linking drought indices to qualitative information within the drought impact database, to linking drought indices to observed and quantifiable impacts including water use restrictions within individual water resource zones. Standardised drought indicators could provide a valuable tool for drought early warning and monitoring, an improved understanding of the links between drought indices and drought impacts could strengthen the utility of drought indicators in operational settings e.g. water resources management.

Exploring the use of long series climate data within operational drought management

Increased understanding of past drought characteristics and impacts can help inform drought management for future droughts. As each drought has a unique set of characteristics, the use of long series data considering a larger number of drought events is valuable to enhance drought risk assessments and model robustness. The use of long series climate data within the water supply sector is beneficial to investigate whether the current modelling period (from 1920) is sufficient for water resources management planning and drought planning. Work by Watts et al. (2012), Todd et al. (2013) and Spraggs et al. (2015) have increased understanding of drought events pre-dating the 1920-2010 analysis period. However, further analysis of historical drought events could be useful to explore drought scenarios that consider more characteristics other than the length of drought durations as recommended in the Environment Agency guidelines.

2.6 Summary

This chapter has discussed the key literature that informs the work undertaken and presented in this thesis. Through the examination of drought indicators, drought propagation, UK drought research and drought management three priority research areas have been identified; (1) investigation of the utility of the Standardised Drought Indices family, (2) linking drought indicators to observed impacts within the water supply system, and (3) exploring the use of long series climate data within operational drought management. These three priority areas have informed the research objectives outlined in section 1.3. In the following chapter the study area is introduced and the data and methods used to address the research objectives are described.

Chapter 3

Study Area, Data and Methods

This chapter introduces and describes the Severn Trent Region and details the data and methods used throughout this thesis

In order to address the aim and objectives outlined in Chapter 1, various climatological and hydro(geo)logical datasets are required. This chapter introduces the thesis study area providing information on the climate, hydrology, and the Severn Trent Water resource system. This follows a detailed description of the, information (rainfall, temperature, evapotranspiration, streamflow, groundwater level and reservoir levels) collated, datasets constructed and how these are processed and methods applied in the analysis of these datasets.

3.1 Severn Trent Region

The thesis focuses on the Severn Trent Region (STR), which combines the areas supplied by Severn Trent Water Ltd, South Staffordshire Water Plc and areas supplying water into STR that lie outside of the formal Severn Trent Water Ltd boundaries (Figure 3.1). The STR covers 21,000km^2 (Severn Trent Water, 2014b), with a variety of landscapes, including rural uplands of the Welsh mountains (rising to over 500 m above ordinance datum (AOD) to the west and the Peak District (rising to over 400 mAOD) to the north, with the English Lowlands to the south and east (*ca*. 0-250 mAOD). Within the lowlands there are several large urban conurbations including Birmingham and the West Midlands that sit in the Birmingham Plateau (>120 mAOD) (Phillips, 2013) and the cities of Leicester, Nottingham and Coventry.

3.1.1 Climate

The STR spans two Met Office UK regional climates, the Midlands and Welsh regions. Annual average rainfall totals in the STR reflect the east-west and southeast to northwest rainfall gradients across the UK (Figure 3.2). Rainfall varies from ~3000mm a^{-1} in the Welsh mountains to less than 600mm a^{-1} around Nottingham. Average annual rainfall in the Peak District exceeds 1000mm a^{-1} reflecting the influence of altitude on rainfall (Phillips, 2013). In the Midlands the distribution of rainfall throughout the year is seasonally well-dispersed, particularly in the east of the region (Kings and Giles, 1997). Areas in the west and north exhibit a more pronounced winter rainfall regime (the wettest months are December and January), resulting from orographic enhancement of frontal rainfall and increased frequency of westerly frontal systems during the winter months (Mayes, 2013). Temperature in the region is less variable than rainfall; annual temperatures vary from 10°C at the highest altitudes of the Peak District and Welsh mountains to 14°C in the lower Severn Valley (around Gloucester) (Met Office, 2016).

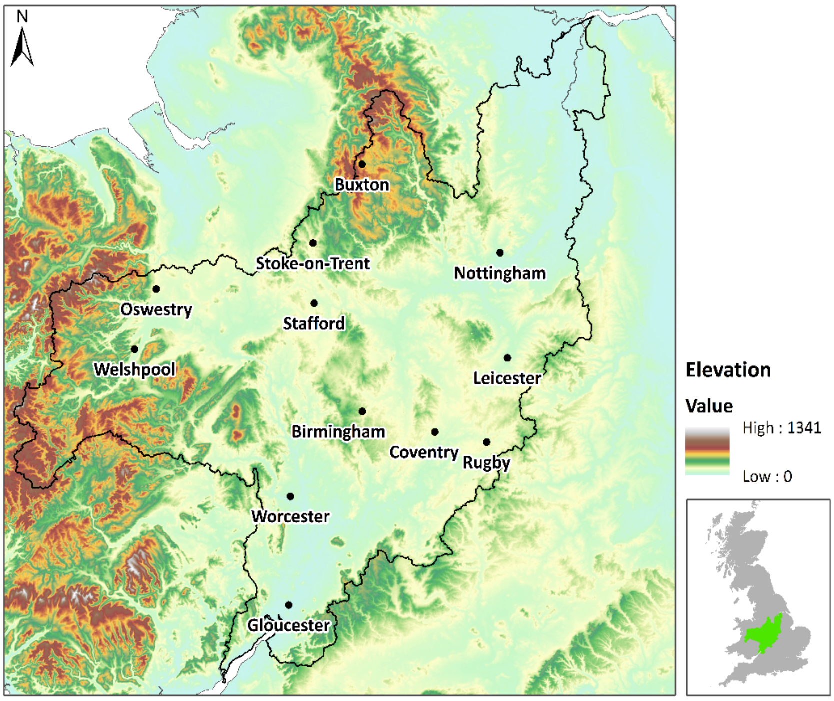

Figure 3.1: The Severn Trent Region including large towns and cities

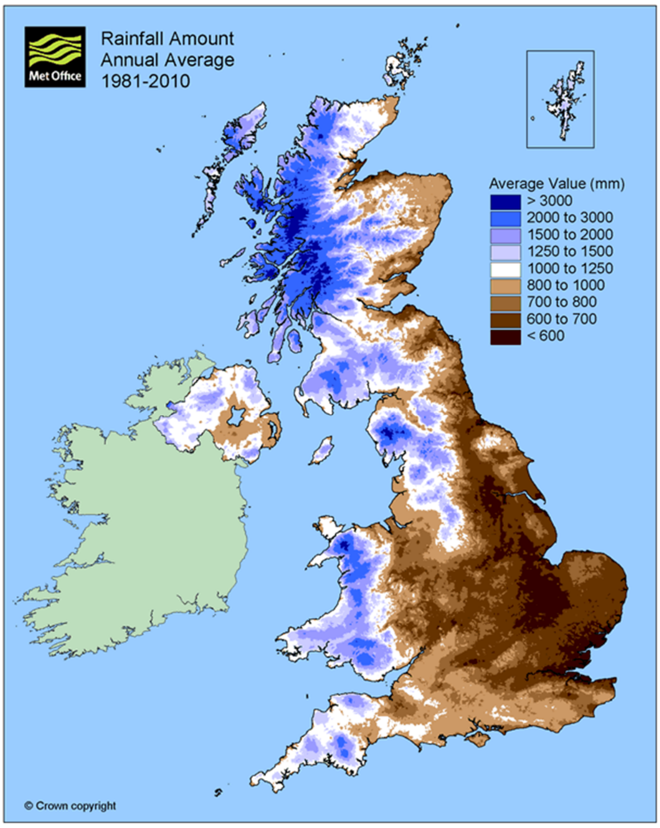

Figure 3.2: Distribution of annual average rainfall across the UK. Source: UK Met Office http://www.metoffice.gov.uk/public/weather/climate

3.1.2 Hydrology

Within the STR there are two major river catchments, the River Severn and River Trent. The River Wye is also an important water source for Severn Trent Water, with the headwaters of the River Wye within the STR, before flowing south and discharging into the Bristol Channel.

River Severn Catchment

The River Severn is the longest river in Britain (354 km) with a catchment area of approximately 11,000 km^2. The source of the River Severn is in the Welsh uplands, it flows south-east through Shropshire, Worcestershire and Gloucestershire into the Bristol Channel downstream of Gloucester. Significant tributaries include the River Avon and the River Teme (Figure 3.2a). Land use in the catchment is predominantly rural, with approximately 90% of land used for agricultural purposes (Environment Agency, 2009). Geology in the catchment is diverse, the Upper Severn is predominantly formed of low permeability Ordovician and Silurian shales and mudstones (Neal et al., 1997), with the Middle and Lower

Severn exhibiting a mixed geology formed of Mudstone, Siltstone and Sandstone of various ages (Collins et al., 1998), with a thick alluvium covering the valley bottoms. Superficial drift deposits across the catchment include outwash gravels, till deposits and river alluvium (Smedley et al., 2005). The geology of the River Avon tributary is predominantly Jurassic and Liassic clays, with highly permeable Permo-Triassic Sandstone present across approximately 16% of the total catchment.

River flows across the Severn catchment are modified by anthropogenic influences including impounding reservoirs, effluent returns, and abstraction for public water supplies, agriculture and industry. During low flow conditions the River Severn is regulated by the Shropshire Groundwater Management Scheme (SGMS); pumped groundwater is used to augment flows in the Severn and its tributaries to balance the needs of abstractors and the environment, the first stage of the SGMS was commissioned in 1984 (Voyce, 2009). The SGMS has been used during the summers of the drought years 1984, 1989, 1995, 1996 and 2006 to supplement river flows with up to an additional 330 mega litres (Ml) of water per day (Voyce, 2009).

River Trent Catchment

The River Trent (Figure 3.2b) is the third longest river in Britain with catchment area of approximately 10,500 km^2. The Trent's source is in the Staffordshire Moors; it then flows north-east through Derbyshire, Leicestershire, Nottinghamshire and Lincolnshire into the Humber Estuary. Significant tributaries of the Trent include the Rivers Derwent, Dove and Soar (Figure 3.2b). Geology in the Trent catchment is diverse, in the higher altitudes of the Peak District Millstone Grit and Carboniferous Limestone are dominant (Jarvie et al., 2000). The lowland areas of the Trent catchment are predominantly alluvial deposits formed from Mercia Mudstone and Permo-Triassic Sandstone (Jarvie et al., 2000).

Land use is dominated by agriculture (70%) (Environment Agency, 2010a), but with large urban areas including Birmingham, Nottingham, Leicester and Derby; ~6 million people live in the Trent catchment. Like the River Severn catchment, the flows in the River Trent catchment are affected by anthropogenic activities including reservoirs, effluent returns, public water supply, agricultural and industrial abstractions (Jarvie et al., 2000).

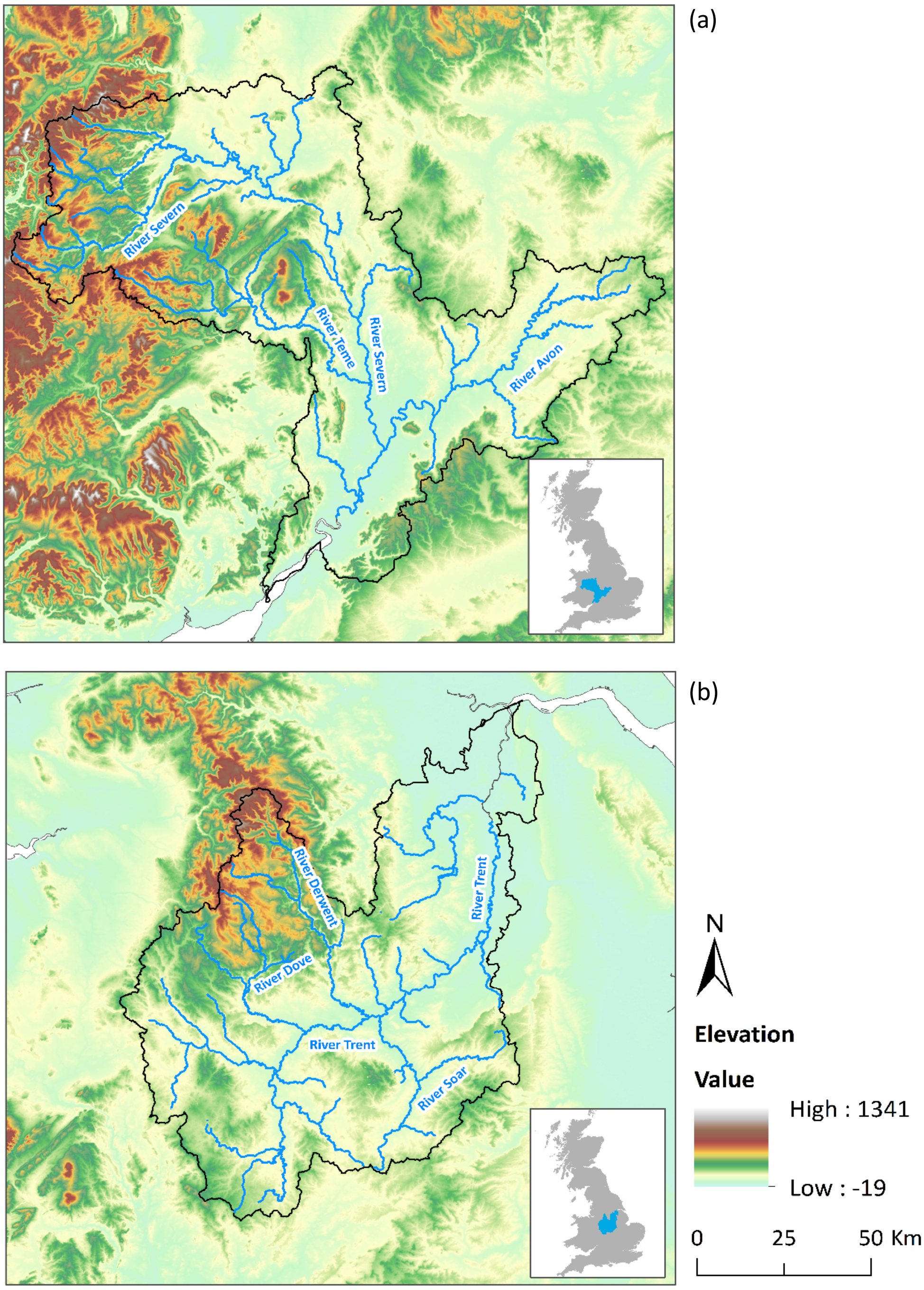

Figure 3.3: (a) River Severn catchment and major tributaries, (b) River Trent catchment and major tributaries

River Wye Catchment

The River Wye catchment is approximately 4,000 km^2 with roughly 440 km^2 of the catchment headwaters within the STR (Figure 3.3). Like the River Severn, the source of the River Wye is in the Welsh uplands and flows into the Bristol Channel. Geology in the catchment is mixed, with impermeable Ordovician and Silurian Shales and Mudstones in the higher elevations (>200 mAOD) and Devonian Sandstones in the areas <120 mAOD, with deep alluvium filling the valley bottoms (Oborne et al., 1980). Land use is primarily agricultural, with only three per cent of the catchment urbanised (Environment Agency, 2010b). Human influences on river flows in the catchment include reservoirs, public water supply, abstractions and effluent returns.

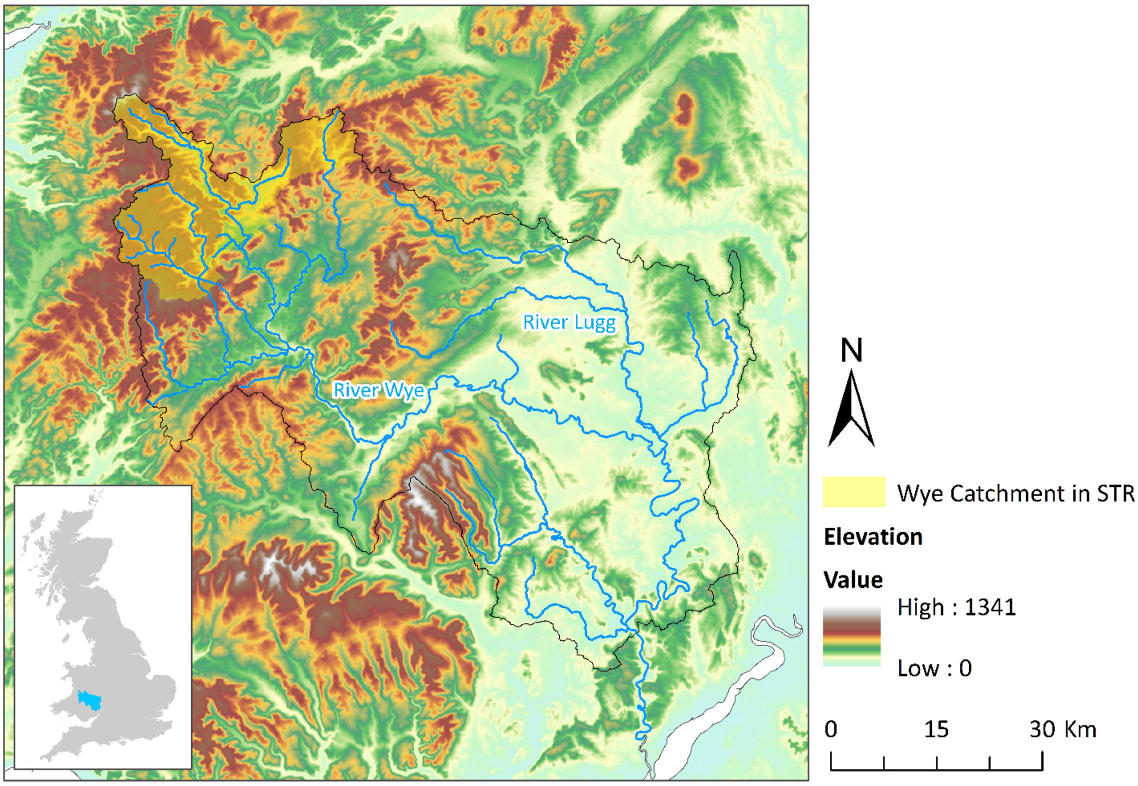

Figure 3.4: River Wye catchment and major tributaries

3.1.3 Hydrogeology

Four major aquifer types are found in the STR; (1) Permo-Triassic sandstone, (2) Jurassic limestone, (3) Magnesian limestone and (4) Carboniferous limestone. The following paragraphs detail the key properties of each of these aquifer types.

Permo-Triassic Sandstone

The Permo-Triassic sandstone group is formed of Permian sandstone and Triassic Sherwood Sandstone Groups. Extensive outcrops are found across the centre and north of the STR. Permo-Triassic sandstone aquifers supply around 25% of groundwater abstractions in the UK (Shepley et al., 2012); they are the second most important aquifer type behind chalk. Transmissivity values in the Permo-Triassic aquifers across the STR range from 2 – 5000m^2/d; flows are both intergranular and through fractures. Transmissivities above 500 m^2/d are thought to be primarily a result of fracture flows (Allen et al., 1997). Sherwood sandstone aquifers in the northern outcrop of the STR are heavily abstracted for spray irrigation, industrial processes and public water supply in Nottingham and Mansfield (Allen et al., 1997).

Jurassic Limestone

Jurassic Limestone aquifers formed of the Great Oolite and Inferior Oolite groups are present to the south and west of the STR. The Oolite limestones are brittle with numerous fissures and fractures, resulting in highly productive aquifers with high transmissivities (3 – 11,000 m^2/d), low storage coefficients and rapid recharge (Allen et al., 1997). Jurassic limestones in the STR are primarily used for public water supplies, but are also an important source for agricultural water requirements (Neumann et al., 2003).

Magnesian Limestone

The Magnesian limestone outcrop found in the north-west of the STR is a highly productive aquifer. Transmissivity (ranging 6 – 4300 m^2/d) is dependent on the extent of fracturing; virtually all flow is through rock fractures (Allen et al., 1997). Groundwater abstractions in the Magnesian limestone provide public water supplies around the Nottingham area.

Carboniferous Limestone

A large Carboniferous limestone outcrop is present in the Peak District in the north of the STR. The properties of this karstic aquifer are complex and have not been studied extensively, but flows are predominantly through solution enlarged fractures (Allen et al., 1997). Interactions with surface waters are substantial, rivers in the in the Peak District are principally fed by springs and direct groundwater discharge into river channels (Edmunds, 1971 as cited in Allen et al., 1997).

3.1.4 Water Resources

Water resources supplied by Severn Trent Water are sourced from river abstractions, impounding reservoirs and groundwater abstractions with each accounting for approximately 33% of total supplies. The STR is divided into 15 water resource zones (WRZ) that vary in size and complexity (Figure 3.5). The Strategic Grid, the largest WRZ, supplies approximately 5 million people, whilst the smallest WRZ serves 8,000 people. Water resource zones are delineated to "identify the largest possible zone in which customers share the same risk of a resource shortfall" (Environment Agency, 2012d). Each WRZ has a different combination of water sources, seven WRZs are conjunctive use zones which are supplied by reservoirs, river abstractions and groundwater abstractions; seven WRZ are only supplied by groundwater and one WRZ is supplied by another water company.

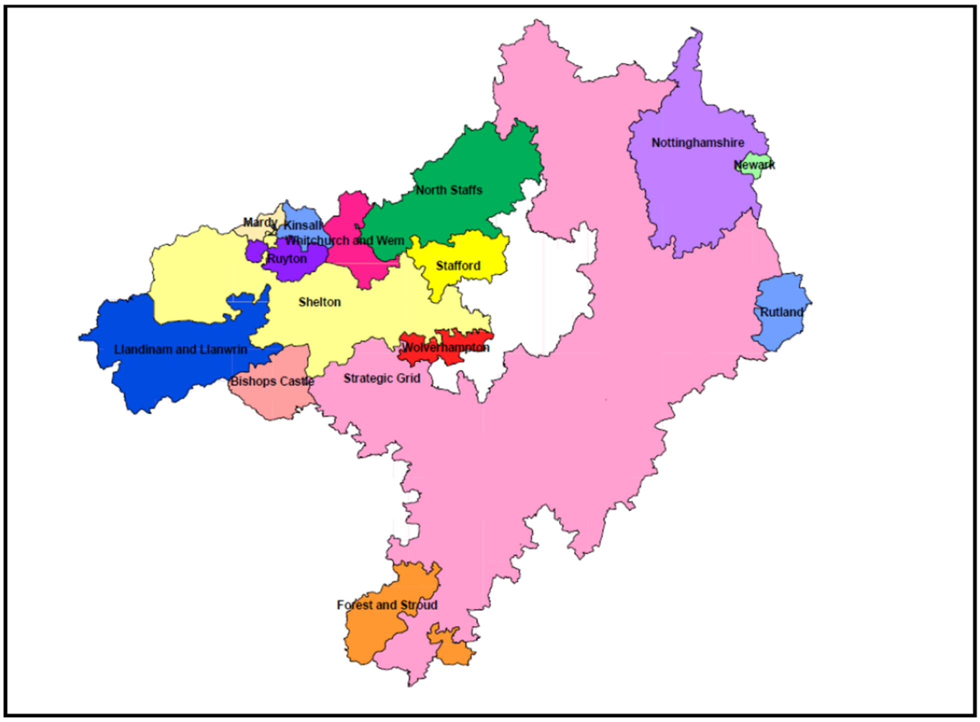

Figure 3.5: Severn Trent Water Resource Zones, Source: Severn Trent Water https://www.severntrent.com/category/586

3.2 Data and Methods

To investigate drought and its impacts on water supply in the Severn Trent Region a wide range of climatological and hydrological datasets are required. Within this thesis rainfall, temperature, streamflow, groundwater and reservoir levels are all used. The following sections describe the data collection, processing and quality control methods used to create a comprehensive dataset to cover the STR.

3.2.1 Rainfall

Rainfall data is an essential component of drought research. This thesis uses rainfall data recorded at meteorological stations across the STR, with the earliest records from 1858. The use of long rainfall series enables a high resolution reconstruction of meteorological drought, which includes a number of drought events commonly analysed in the UK as benchmark events. In total 15, rainfall series are constructed to represent the STR area, eight long-series records (1858-2012) and seven short series (1962-2012) to analyse meteorological droughts (Figure 3.5; Table 3.1).

Historic Rainfall Data in the UK

The UK has a wealth of historic meteorological observations; during the seventeenth and eighteenth centuries sites of instrumental weather observation expanded across Europe. In the UK, the Royal Society and interested individuals began to record daily meteorological observations including rainfall, temperature and wind (Kington, 1997). The first temperature readings were recorded at Upminster in 1697 by William Derham (Met Office, 1961), and the earliest rainfall readings taken by Richard Townley in 1677 at Burnley (Jones, 2001). The number of observations expanded and from 1860 (until 1899) rainfall measurements collected across the UK were compiled by G. J. Symons into *Symon's British Rainfall* an annual report of rainfall totals and distribution across the British Isles. These records and the rainfall data collected were purchased by the Met Office in 1919 (Pedgley, 2010) and today, digitised historical rainfall records can be accessed through the Centre for Environmental Data Analysis (CEDA), British Atmospheric Data Centre (BADC) and the Met Office Integrated Data Archive System (MIDAS) (Met Office, 2012), though many historical weather records remain untranscribed or digitised. Tabony (1980) used numerous historic rainfall records to construct long homogenous composite rainfall series for Europe, including 40 sites in the UK. These records are available through the University of East

Anglia's Climate Research Unit (CRU) and have been extensively used in climatological and hydrological research (e.g. Jones and Lister, 1998; Todd et al., 2014; Burt et al., 2015; Spraggs et al., 2015).

The most recent addition to historic rainfall data availability in the UK is the CEH-Gridded Estimates of Areal Rainfall (CEH-GEAR). This dataset uses the Met Office rainfall database to produce 1 km gridded areal monthly and daily rainfall; data is available from 1890. However, the spatial coverage of the rain gauge network for 1890 is sparse, therefore use of the dataset prior to 1961 is cautioned, with the need to consider the distance between the grid and the nearest rain gauge (Keller et al., 2015). Whilst this dataset could provide a useful dataset to analyse historic drought spatially across the UK, it was not available until early 2015 therefore, its use in this thesis was not feasible.

Construction of Rainfall Series

The rainfall data used in this thesis can be divided into two types by the length of the record; (1) long-series that start between 1858 and 1900 ending in 2012 (Table 3.1a) and (2) more recent data that start in 1962 and end in 2012 (Table 3.1b). It was decided that the datasets used within this thesis would be consistent, therefore whilst some additional years have subsequently become available in some series, the final data collection point would be the end of 2012. The rainfall series were constructed using the BADC MIDAS UK Daily Rainfall Data (Met Office, 2006) accessed through CEDA. Data in MIDAS were quality control checked by the Met Office to ensure data were correct and consistent with surrounding rain gauges.

The following steps were used to construct all rainfall records used in this thesis:

1) The BADC MIDAS UK Daily Rainfall Data (Met Office, 2012) metadata were examined to identify the most suitable and complete records. Sites with more than 20% missing data are rejected. An interactive Google Earth layer was used to identify rain gauge locations and station metadata available from MIDAS. The metadata includes information on missing data, dates of commissioning and decommission, location co-ordinates and elevation.

2) Data gaps were present in each of the records, therefore additional selection criteria include the availability of nearby rain gauges (secondary) (within 10 km) to provide suitable secondary rainfall data to bridge gaps in the primary rainfall data. These secondary data had specific selection criteria: (1) distance <10km from primary rain

gauge, (2) suitable overlap period of at least 2 years prior to missing data and (3) the coefficient of determination (R^2) value between the primary and secondary rain gauges for the overlapping period was >0.7. The length of the overlap between the primary and secondary stations was a key consideration in the selection of secondary stations (Tabony, 1983).

3) Quality control checking of the data to remove duplicate entries and erroneous data required significant data processing. Errors in the CEDA MIDAS system script (Winfield, 2015) results in some sporadic duplicate entries; whilst most duplicate data entries contain identical rainfall values others contain the total rainfall accumulated over a number of preceding days (up to one month). These entries can be identified using two code markers. The first code marker that indicates the status of quality control checking- 0 indicates the data has not been checked and 1 indicates quality control checks have occurred. The second code marker indicates how many days the data has been accumulated over.

4) Gaps were filled using data from nearby weather stations. Regression imputation was used to estimate missing data based on the regression relationship between the primary and secondary rain gauges (Tabony, 1983; Rubin and Little, 2002). The regression relationship between the primary and secondary stations was calculated and used to apply adjustment factors to the secondary rainfall values for each day of missing data in the primary rainfall record.

5) The re-constructed rainfall series were checked for homogeneity, trend and randomness. The Distribution-Free CUSUM (Appendix A, Equation 1) was used to test for step jumps in annual mean. The Mann-Kendall test (Appendix A, Equation 2) was used to check for artificial trends that could result in inhomogeneous data. Randomness was assessed using the Rank Difference test (Appendix A, Equation 3).

Rainfall sites were selected based on good spatial coverage of the STR that reflects the rainfall gradients (east to west and the southeast to northwest) and the range of altitudes within the region. The highest rain gauge (Clywedog) is situated at 290 m AOD and the lowest (Balderton) is at 17 m AOD. The long rainfall records provide a useful dataset to reconstruct historic drought. Whilst the spatial coverage is not extensive these sites represent a range of elevation and spatial distribution of rainfall across the STR. Some of the rain gauges are situated near key water supply reservoirs; these include Rhayader near the Elan Valley Reservoir Group and Wall Grange near Tittesworth Reservoir. The mean annual rainfall values presented in Table 3.1 are for the WMO 30-year standard period 1971-2000. The 1971-2000 30-year climate period has been chosen over the 1961-1990 period as the data in Table 3.1b start in 1962.

Table 3.1a: Reconstructed long series rainfall series (1858-2012). Mean annual rainfall values for the period 1971-2000.

Station Name	BADC ID	Latitude	Longitude	Elevation (m OSL)	Start Date	Mean Annual Rainfall (mm)
Rhayader	10439	52.311	-3.515	268	1858	1688
Chatsworth	544	53.227	-1.609	133	1858	843
Weston Park	9934	52.694	-2.286	113	1858	726
Rugby	604	52.369	-1.255	117	1872	649
Wall Grange	3188	53.079	-2.051	139	1882	922
Nanpantan Reservoir	3470	52.749	-1.246	82	1887	714
Oakly Park	10067	52.381	-2.747	91	1900	744
Nottingham	559	52.949	-1.153	59	1900	612

Table 3.1b: Reconstructed rainfall data 1962-2012. Mean annual rainfall values for the period 1971-2000.

Station Name	BADC ID	Latitude	Longitude	Elevation (m OSL)	Start Date	Mean Annual Rainfall (mm)
Balderton	3587	53.055	-0.770	17	1962	565
Clywedog	16800	52.470	-3.604	290	1962	1720
Llanforda	9797	52.858	-3.086	216	1962	943
Taynton	10354	51.892	-2.374	24	1962	703
Wellesbourne	596	52.205	-1.603	47	1962	594
Welshpool	9717	52.657	-3.131	70	1962	783
Whitacre	3067	52.516	-1.681	73	1962	664

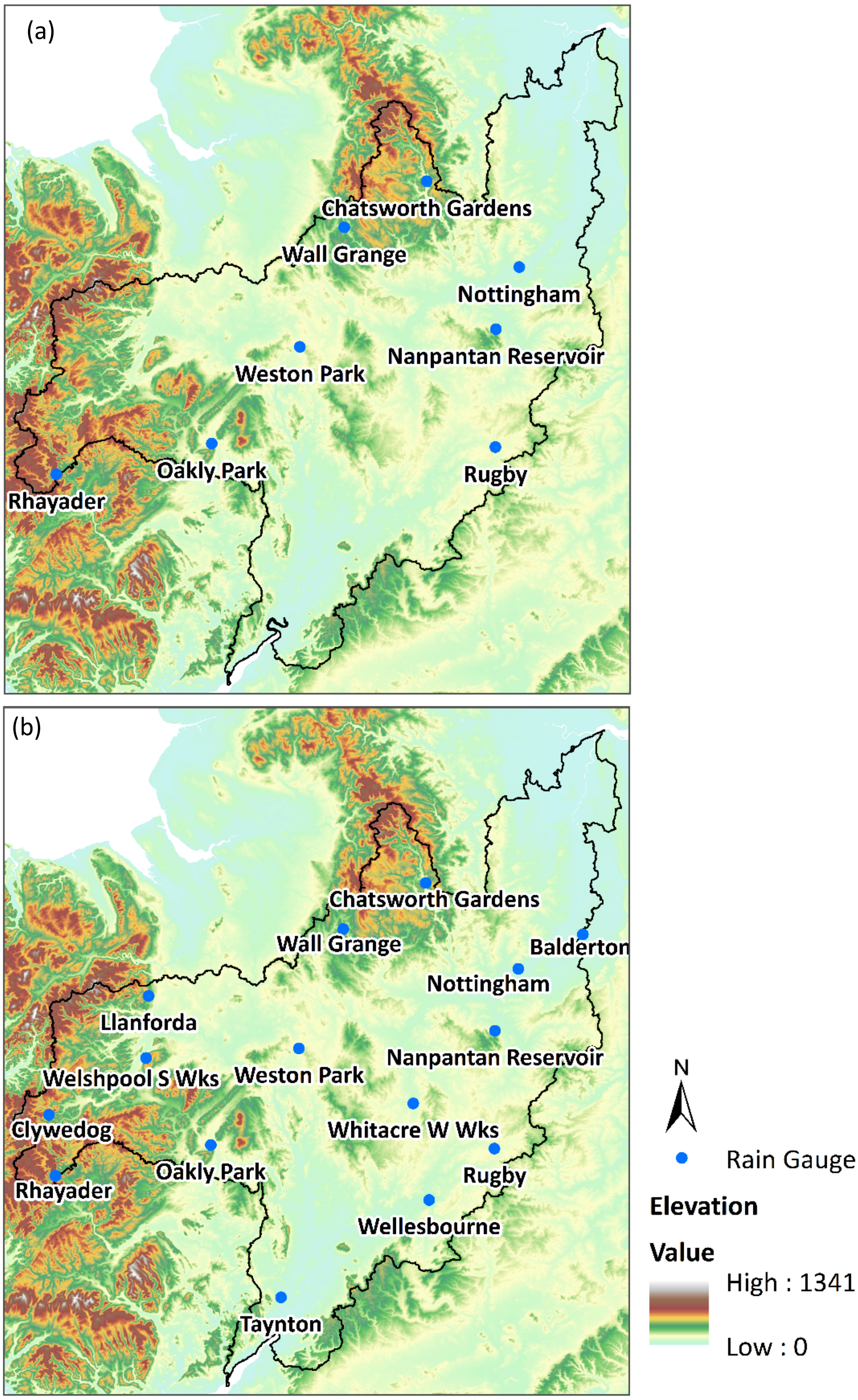

Figure 3.6: Location of rain gauges across the STR (a) long series rain gauges starting before 1900 (b) shorter series rain gauges (1962-2012)

3.2.2 Temperature

The Met Office's, Hadley Centre, Central England Temperature (HadCET) series is one of the longest instrumental temperature records in the world. Originally created by Manley (1953) the Central England Temperature series was adopted by the Met Office; it is maintained to the present day and freely available through the Met Office (http://www.metoffice.gov.uk/hadobs/hadcet/). Mean monthly temperature records date back to 1659, with mean daily temperatures available from 1772 and daily minimum and maximum values available from 1878. The CET series is constructed from multiple regional temperature series representative of central England, based roughly on a triangle from the Lancashire Plain in the north, London to the south-east and Bristol to the south-west (Karoly, 2006). As most of the Severn Trent Region falls within the CET measurement zone, it is assumed to be representative of temperature across the much of the study region. The CET may be less applicable to upland Wales however, where limited long temperature records are available (Macdonald et al., 2010). The CET series is used for the entire STR, in the absence of long historical temperature records for upland Wales. Throughout the thesis various versions of the CET are used- mean, minimum and maximum monthly data.

3.2.3 Evapotranspiration

Evapotranspiration data are used in this thesis for the computation of the SPEI and hydrological modelling. Potential Evapotranspiration (PET) is defined as the amount of evapotranspiration that would occur assuming no restriction on the supply of water. There are a number of equation based methods of using meteorological variables to estimate PET with differing complexities and data requirements. The Thornthwaite (1948) equation (Appendix A, Equation 4) estimates PET on a monthly basis. It is one of the simplest and commonly used PET estimation methods, requiring only mean monthly air temperature and latitude of the site of interest. Latitude is required to estimate day length and sun angle.

In this thesis PET is estimated at each rainfall site. The minimal data requirements make the Thornthwaite PET methodology particularly useful in long-series climatological studies where limited meteorological data are available (Bradzil et al., 2015). The Thornthwaite equation was used in the original SPEI methodology formulated by Vicente-Serrano et al. (2010). The Penman-Monteith equation recommended by the World Meteorological Organisation (WMO) and Food and Agriculture Organisation of the United Nations (FAO-UN), requires a number of additional meteorological observations (or estimates of) including daily minimum and maximum temperature, wind speed, vapour pressure and net radiation, which are unavailable for longer series. However, the potential limitations of the Thornthwaite method are recognised, as Kenny and Harrison (1992) found the Thornthwaite equation tends to overestimate PET in European latitudes (~50°N) compared to the Penman-Monteith equation.

3.2.4 Streamflow

Streamflow data are required to investigate the propagation of meteorological drought into the terrestrial component of the water cycle and to examine the relationship between meteorological and hydrological drought indicators. Streamflow data in the UK are compiled, quality control checked and accessed through the Centre for Ecology and Hydrology's National River Flow Archive (NFRA) (http://nrfa.ceh.ac.uk/data/search). The NFRA holds daily, monthly and flood peak discharge data from over 1500 gauging stations across the UK. In this thesis discharge data from 15 gauges (Table 3.2, Figure 3.6) on ten different rivers within the Severn, Trent and Wye catchments (outlined in 3.1.2) are selected for analysis.

Gauge selection

Gauge selection was based on the following criteria; (1) record length, (2) extent of flow modification and (3) percentage of missing data. In order to capture a number of droughts all records must have started prior to at least 1975 to capture the last three significant drought events (1975, 1995 and 2012). The level of flow modification resulting from anthropogenic influences on the rivers across the STR is substantial. The gauged records have been partially selected based on the level of flow modification, particularly sites that are described as having natural flows up to Q_{95}. This was to capture hydrological drought response with no or little anthropogenic influence. However, there are very few UK rivers that have such little anthropogenic influence, so a number of the gauging stations selected are subject to flow modification. These discharge records also allow the investigation of hydrological drought across more of the study region and reflects hydroclimatological and anthropogenic influences during low flows. The final selection criterion was the selection of records that have no more than 3% missing data and that any missing data did not cover a drought event.

Infilling Missing Data

Of the15 gauges selected, seven contained missing data:

1) Llanyblodwel (54038)- 153 days (01/05/1984 – 30/09/1984)
2) Ddol Farm (55026)- 59 days (01/01/1963 – 28/02/1963)
3) Wedderburn Bridge (54017)- 47 days (29/03/2001 – 14/05/2001)
4) St Mary's Bridge (28085)- 15 days (08/03/1937 – 22/03/1937)
5) Hookagate (54018)- 8 days (21/03/1978 – 28/03/1978)
6) Ilam (28031)- 1 day (30/04/1968
7) Bewdley (54001)- 1 day(10/02/1946)

Missing gauged data were simulated using the rainfall-runoff model IHACRES, available through eWater Toolkit (http://www.toolkit.net.au/tools). IHACRES, is a catchment scale rainfall-runoff model designed to capture the dynamic relationship between rainfall and discharge using rainfall and temperature data (Croke and Jakeman, 2004). Daily records of temperature, rainfall and discharge were used to calibrate the model and simulations were computed using rainfall and temperature data. Daily rainfall data used in each simulation was provided by the nearest and most appropriate rainfall station from those outlined in section 3.2.1. In most cases the selected rainfall station was within the boundary of the catchment streamflow record that required infilling. However, the nearest rainfall stations are not necessarily within the same catchment as the station that required the gap filling. To ensure the rainfall data would provide a reasonable representation of rainfall for each catchment, mean annual rainfall values were compared against catchment mean annual rainfall provided through the metadata for each catchment in the NFRA. Daily temperature data was provided by the CET mean daily record. Goodness-of-fit was tested using the Nash-Sutcliffe Efficiency (NSE) (Appendix A, Equation 5), all NSE values were greater than 0.73 indicating that the simulated data is acceptable. Santhi et al. (2001) suggest that NSE values greater than 0.7 indicate acceptable model simulations. The gaps in discharge data at sites 28031 and 54001 are only one day so these gaps were filled using linear interpolation between the preceding and proceeding days (Appendix A, Equation 6).

Table 3.2: Discharge data and catchment information

Station Name	NFRA ID	River	Catchment Area (km^2)	Start Date	Percent Complete	Daily Q_{95} (m^3/s)	Daily Q_{50} (m^3/s)
Izaak Walton	28046	Dove	83	1969	100%	0.54	1.62
Rocester Weir	28008	Dove	399	1953	100%	1.76	5.3
Marston on Dove	28018	Dove	883	1961	100%	3.61	9.86
Ilam	28031	Manifold	148	1968	>99%	0.63	2.35
St Mary's Bridge	28085	Derwent	1054	1936	>99%	4.58	11.8
Tenbury	54008	Teme	1134	1956	100%	1.55	8.35
Knightsford Bridge	54029	Teme	1480	1970	100%	1.97	10.1
Walcot	54012	Tern	852	1960	100%	2.27	4.87
Rodington	54016	Roden	259	1961	100%	0.40	1.19
Wedderburn Bridge	54017	Leadon	293	1962	>99%	0.30	1.00
Hookagate	54018	Rea Brook	178	1962	97%	0.23	0.90
Llanyblodwel	54038	Tanat	229	1973	98%	0.60	3.85
Ddol Farm	55026	Wye	174	1937	>99%	0.55	3.67
Stareton	54019	Avon	347	1962	100%	0.48	1.35
Bewdley	54001	Severn	4325	1921	>99%	10.67	36.35

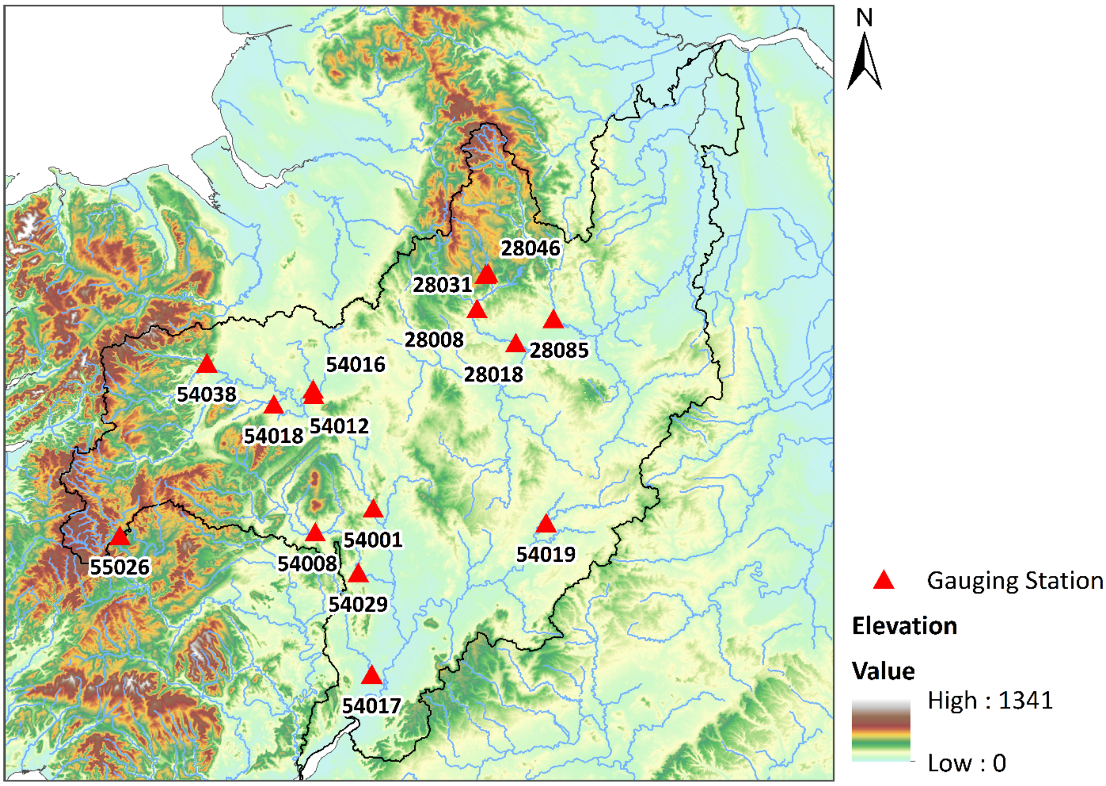

Figure 3.7: Location of gauging stations in the STR

3.2.5 Groundwater

Ten groundwater level records are used in this thesis (Table 3.3), these records cover the four main aquifer types present in the STR outlined in section 3.1.3 (Figure 3.7). The data is provided by the British Geological Survey (BGS) and Environment Agency (EA). These groundwater records are in the observation borehole network, sites are monitored regularly to provide time-series data from boreholes where the impacts of significant groundwater abstraction are limited. Four of the boreholes within the STR (Table 3.3) are used as index wells in the Hydrological Summary of the UK which provides monthly analysis of national and regional hydro(geo)logical trends.

Whilst the data supplied by both the BGS and EA provided a continuous time-series of groundwater level data, which is typically measured at daily or weekly intervals, the frequency of measurement was not consistent between the boreholes and also within a single record. To create continuous, comparable records the data were processed to provide a consistent monthly time-step. The monthly records were developed by extracting a single water level data point in the last week of each month typically between the 25th and 31st days. The last week of the month was selected as a review of data availability for each borehole record revealed that data collection frequency tended to be highest during this period. Eight of the ten records contained missing data, these gaps were filled using linear interpolation (Appendix A, Equation 6) based on the data of preceding and proceeding months.

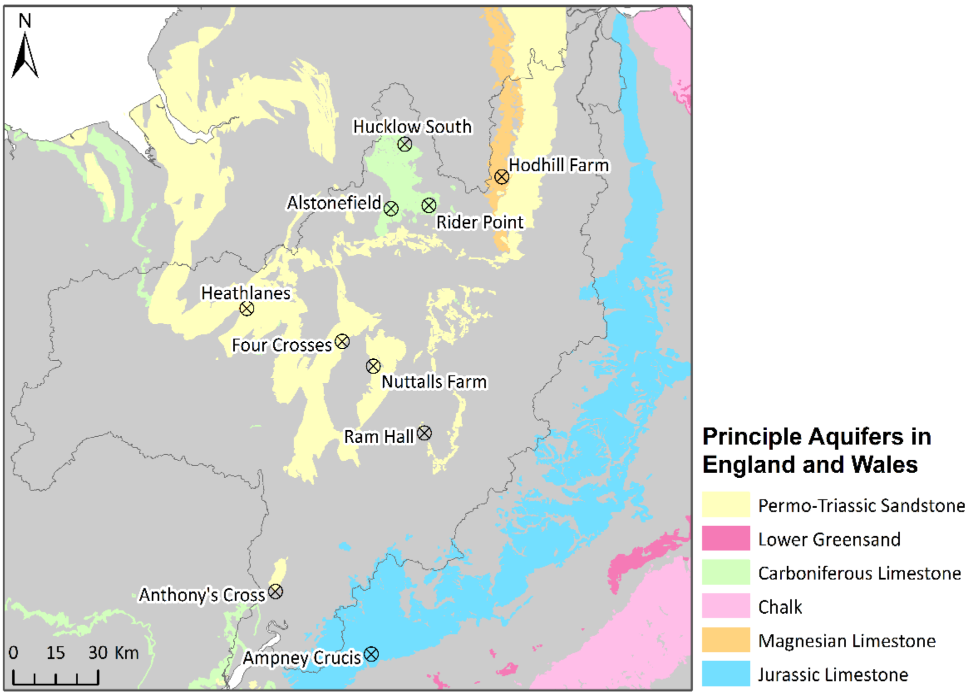

Figure 3.8: Groundwater level sites in the Severn Trent Region and principle aquifer types in England and Wales

Table 3.3: Details of groundwater level data (* denotes BGS observation boreholes)

Site Name	Aquifer Type	Start Date	Percent Complete	Well Depth (m)
Alstonefield*	Carboniferous Limestone	1974	99%	137
Ampney Crucis*	Jurrasic Limestone	1959	99%	61
Anthony's Cross	Permo-Triassic Sandstone	1973	98%	11
Four Crosses	Permo-Triassic Sandstone	1971	98%	49
Heathlanes*	Permo-Triassic Sandstone	1971	100%	8
Hod Hill Farm	Magnesian Limestone	1972	98%	48
Hucklow South	Carboniferous Limestone	1969	96%	123
Nuttalls Farm*	Permo-Triassic Sandstone	1974	100%	14
Rider Point	Carboniferous Limestone	1976	96%	98
Ram Hall	Permo-Triassic Sandstone	1973	97%	17

3.2.6 Reservoir Levels

Accessing reservoir level or storage data in England and Wales is a challenge. As a result of privatisation of the water industry there is no formalised reservoir level data collection that is (1) at the national level or (2) publicly available. Each water company maintains their own reservoir data, however, various changes in the provision of potable water in England and Wales as detailed in section1.2 have resulted in fragmented records of reservoir data. At Severn Trent Water a limited amount of reservoir level data was digitally available for the recent past (1999 onwards) or for specific periods, such as the 1995-96 drought. Data of this length contains few drought events and cannot appropriately capture sufficient information to establish the links between meteorological drought, hydrological drought and the associated impacts on water supply reservoirs.

To construct longer records of past reservoir levels archived paper records have been located, digitised and subsequently transcribed (Figure 3.8a). The records for 12 reservoirs are accessed through a database of scanned weekly water level data; the original paper records appear to be been destroyed by Severn Trent Water after scanning. Of these 12 reservoirs, six have been transcribed. Examination of the records for the remaining reservoirs identifies a number of large periods of missing data. Paper copies of daily reservoir level data for the Elan Valley Reservoir Group are available in the operational office archive at Elan Valley from 1963 to 2002 (Figure 3.8b). These records detail the daily water levels at the four reservoirs that form the Elan Valley Group- Caban-coch, Pen-y-garrag, Craig-goch and Claerwen. These records were photographed and transcribed into a digital database to create a new database of reservoir level data. All records prior to the early 1980s are recorded in imperial feet and inches, these are converted to metres to match data recorded with the metrication of the water supply system. The reservoir level data in metres below top water level (MBTWL) are converted into reservoir storage volumes based on the water level-storage relationship for each reservoir obtained from Severn Trent Water.

Data from the six transcribed reservoirs (Table 3.4, Figure 3.9), are a mixture of on-stream impounding and off-stream pump storage reservoirs. Four of the reservoir level series contained missing data that are filled using linear interpolation based on the preceding and proceeding data (Appendix A, Equation6). The capacity of the reservoirs/ reservoir complex varies from 2528 Ml to 99499 Ml. The Elan Valley Group and Derwent Valley Group are both formed of a series of reservoirs that supply water for the largest and most populous water resource zone in the STR- known as the Strategic Grid. These series are not included within the appendices of this thesis, as they now represent part of the Severn Trent archives, with this work undertaken whilst at Severn Trent.

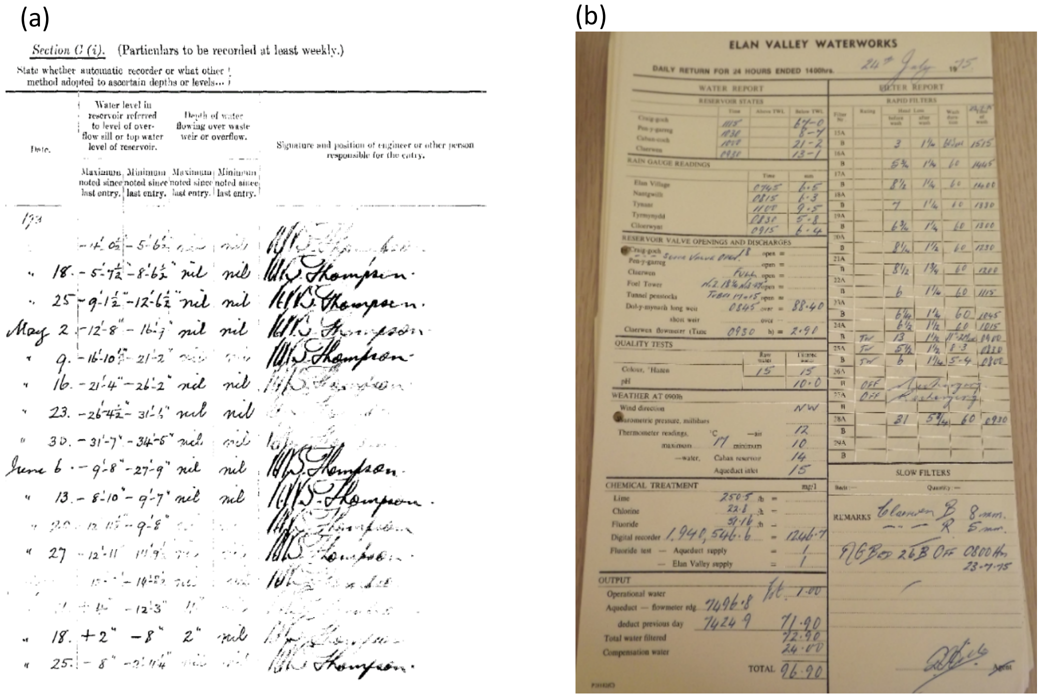

Figure 3.9: Examples of archived reservoir level data (a) scanned in weekly records from Derwent Reservoir (Derwent Valley Complex) 1939; (b) photographed daily records for Elan Valley Reservoir 1975

Table 3.4: Details of digitised reservoir level records. Percentage complete for monthly data.

Reservoir	Capacity (Ml)	Start Date	Reservoir Type	Percent Complete
Elan Valley Group	99499	1963	Impounding	>99%
Derwent Valley Group	46345	1946	Impounding	100%
Carsington	36331	1991	Pump Storage	98%
Tittesworth	6440	1983	Impounding	100%
Ogston	6050	1960	Pump Storage	98%
Cropston	2528	1931	Pump Storage	98%

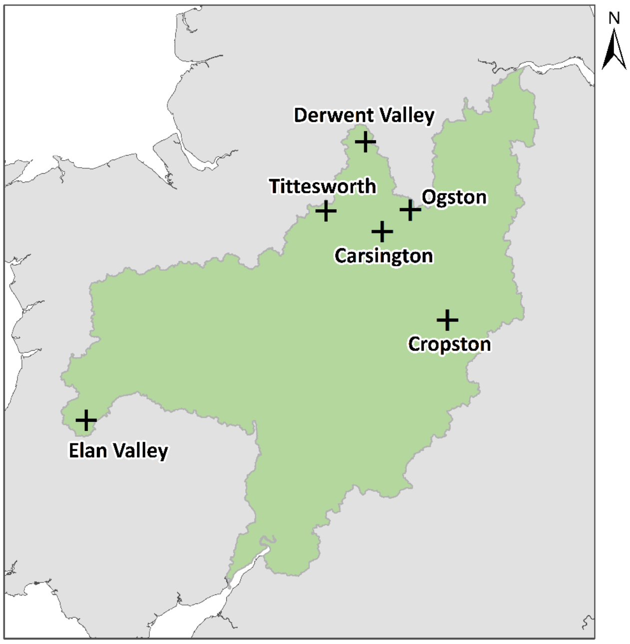

Figure 3.10: Location of reservoirs with digitised water level data

3.2.7 Atmospheric Circulation Indices

Three large-scale atmospheric climate drivers are used in investigation of their links to meteorological drought; these are; (1) Atlantic Multidecadal Oscillation (AMO), (2) North Atlantic Oscillation (NAO), and (3) East Atlantic-Western Russia (EA-WR).

AMO

The AMO is a mode of variability in the North Atlantic Ocean that influences sea surface temperatures over a period of ~50 – 70 years (Kerr, 2000). The AMO index used in this thesis is derived from the Extended Reconstructed Sea Surface Temperature (ERSST) v3b dataset of global monthly sea surface temperature analysis and is available through the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer. The AMO index based on the average of monthly sea surface temperature anomalies and is computed on a monthly timescale from 1854 – present day (https://climexp.knmi.nl/data/iamo_ersst_ts.dat).

NAO

The NAO is a dominant mode of atmospheric variability across the mid- and high-latitudes of the northern hemisphere which results from the switching of atmospheric sea-level pressure between the Arctic and the subtropical Atlantic (Hurrell et al., 2003). Whilst the NAO can be derived using a number of methods, the NAO index used in thesis is available from the Climatic Research Unit at the University of East Anglia). This version of the NAO index is based on the normalised pressure difference between Gibraltar and south-west Iceland on a monthly timescale (Jones et al., 1997) which extends back to 1823(https://crudata.uea.ac.uk/cru/data/nao/nao.dat).

EA-WR

The EA-WR circulation pattern is another dominant teleconnection that influences climate variability over Europe, it is characterised by two anomaly centres over the Caspian Sea and Western Europe (Barnston and Livezey, 1987). The EA—WR index is derived from the application of an orthogonally rotated principal component analysis (RPCA) to normalised monthly geopotential-height at 500-hPa anomalies which is then re-normalised to match the 1981-2010 monthly mean baseline. The data are available through the US National Oceanic and Atmospheric Administration's Climate Prediction Centre (ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/eawr_index.tim).

3.3 Drought Characterisation

The complex nature of drought makes quantifying or describing its state a challenge; drought indices provide a framework to define, analyse and monitor drought events (Panu and Sharma, 2009; Mishra and Singh, 2010; Sheffield and Wood, 2011). Drought indices have been extensively discussed in section 2.2, the following sections detail the computation of drought indices used throughout this thesis- SPI, SPEI and non-parametric standardised drought indices.

3.3.1 Standardised Precipitation Index (SPI) and Standardised Precipitation Evaporation Index (SPEI)

The following sections detail the computation of the SPI and SPEI; both of these indices use a similar methodological framework with the primary difference being the SPI is simply the transformation of rainfall data, whereas the SPEI is the transformation of the climatic water balance (defined as rainfall minus evapotranspiration). The SPI and SPEI are calculated for the following accumulation periods (the number of months rainfall/ water balance is summed over) 1-, 3-, 6-, 9-, 12-months. These accumulation periods are selected in an attempt to reflect the timescales at which drought could be manifest in soil moisture, streamflow, reservoirs and groundwater levels (McKee et al., 1993).

The first step in the calculation of the SPI/SPEI is to determine the most appropriate probability distribution that fits the rainfall/water balance for each accumulation period. The SPI and SPEI can be calculated for a number of different probability distributions. Distributions tested to fit rainfall data for the SPI are gamma, Weibull, Gumbel, logistic, log-normal and normal. These are chosen based on previous studies (Lloyd-Hughes and Saunders, 2002; Sienz et al., 2012, Stagge et al., 2015b). Distributions fitted for the SPEI climatic water balance are generalised extreme value (GEV); Pearson Type-III (PE3) and generalised logistic (Gen Log); these are chosen based on the methodologies of Vicente-Serrano et al. (2010); Gocic and Trajkovic (2014); Stagge et al. (2015b). In the original SPEI methodology by Vicente-Serrano et al. (2010) a three parameter log-logistic was recommended as the most suitable distribution to transform climatic water balance data; the Gen Log distribution is equivalent to the three parameter log-logistic distribution (Stagge et al., 2015b). Whilst, Stagge et al. (2015b) suggest that the gamma distribution is the most appropriate distribution to compute the SPI and the GEV for the SPEI across Europe. It is still necessary to assess the suitability of each distribution outlined above for the data used in the thesis. Distribution fitting is executed in R using the `fitdistrplus` package (Delignette-Muller et al., 2014). The `fitdist` function is used to fit each distribution using maximum-likelihood estimation (MLE). Some additional code is written to define the Gumbel probability distribution to use with this package (Appendix B, Code 1).

The goodness-of-fit (GOF) between the distribution of the accumulated data and the candidate theoretical distribution is tested using the Anderson-Darling test (A-D) (Equation 7, Appendix A) and the Shapiro-Wilks test (S-W) (Appendix A, Equation 8). The A-D test is calculated using the `gofstat` function in the `fitdistrplus` package and the S-W test is calculated using the `EnvStats` package (Millard, 2015). All these statistical tests can be used to measure the discrepancy between empirical and theoretical distributions. Critical values for the A-D test must be calculated for each candidate distribution, the `qualityTools` package is used to compute critical values using the `adSim` function (Roth, 2015). The `adSim` function uses a bootstrapping procedure to resample the data a specified number of times to calculate critical values for the following quantiles- 0.75, 0.90, 0.95, 0.975 and 0.99).

The Aikake's Information Criterion (AIC) is also used to assess the fit between accumulated data and candidate distributions. However, unlike the A-D and S-W tests, AIC is not a statistical GOF test, but assesses the relative fit between each candidate distribution (Stagge et al., 2015b). AIC is calculated for each site and accumulation period using the `gofstat` function in the `fitdistrplus` package. The AIC value for each distribution (AIC_i) was used to calculate AIC Differences (AICD) (Appendix A, Equation 9) as recommended in Burton and Anderson (2002) and Sienz et al. (2012). The best fit distribution has an AICD = 0. $AICD_i$ values >10 indicate there is essentially no support for the fit of a theoretical distribution, $AICD_i$ values between 4 and 7 indicate considerable support and $AICD_i$ values between 0 and 2 indicate substantial support.

Graphical checks are also used to ensure the data fit candidate distributions sufficiently, particularly in the tails of the data. Whilst statistical tests to assess GOF are useful, graphical methods can provide vital information that statistical GOF test cannot (Hensel and Hersch, 2002). Quantile-quantile plots (QQ-plots) show the empirical quantiles of the observed data against corresponding quantiles of the specified theoretical distribution; they are a useful graphical tool that have been extensively used to assess the fit of data to specified distributions (Gan et al., 1991).

Wu et al. (2005) highlight the issue of using data of different lengths when computing the SPI, particularly the influence of record length on the shape and scale parameters of the probability distribution function used. Throughout this thesis, the SPI is calculated for multiple periods of time based on the length of records under investigation. However, all analyses use consistent time periods (e.g. 1858-2012, 1900-2012, 1962-2012) for distribution fitting and SPI computation to ensure drought characteristics can be examined with consistency.

Once the suitable probability distributions for each accumulation period have been established the SPI/SPEI can be calculated for each accumulation period (1-, 3-, 6-, 9-, 12-months). The SPI and SPEI are calculated in R using the `SCI` package (Gudmundsson & Stagge, 2014). The computation was divided into two functions (1) `fitSCI` and (2) `transformSCI`. The `fitSCI` function estimates distribution parameters specifying the best-fit distributions established in the distribution fitting stage. The `transformSCI` function transforms the rainfall/water balance data specified distribution to a normal distribution and assigned SPI values to each month. The original SPI equation is presented in Appendix A, Equation 10.

3.3.2 Non-parametric Standardised Drought Indicators (np-SDI)

The non-parametric SDI offers an alternative approach for monitoring and characterising droughts to the standardised drought indices (SPI, SPEI, SSI, SGI) outlined in section 2.2. The main advantage of the non-parametric SDI approach is the use of a normal scores transformation to compute drought indices based on the rank of each observation time-step for each variable of interest e.g. rainfall, streamflow, groundwater, soil moisture and reservoir storage. This method is based on the work of Bloomfield and Marchant (2013) who used a similar approach to create a standardised groundwater index methodology that overcomes the issue of fitting irregular groundwater level data to specific probability distributions. Bloomfield and Marchant (2013) found that a wide range of different distributions had to be used to fit the groundwater data; this creates uncertainty that the standardised parametric drought indices method can be used to compare different groundwater records objectively. The non-parametric SDI provides a methodology to calculate consistent drought indices of each variable of interest. The non-parametric SDI is calculated by applying a rank-based inverse normal transformation (RIN) using the inverse cumulative distribution function with the Rankit method (Appendix A, Equation 11). This approach is used because the RIN transformation can convert any continuous population distribution to an approximately normal distribution (Beasley et al., 2009). Using this method any SDI calculation will pass the K-S test for normality. In this thesis, this method is used to compute the non-parametric SPI (np-SPI), standardised streamflow index (SSI), standardised groundwater index (SGI) and a standardised reservoir index (SRI). Although the acronym 'SRI' was used in Chapter 2 for the standardised runoff index, it is used for the standardised reservoir index throughout the rest of this thesis. The SGI, SSI and SRI are computed only at a 1-month timescale due to serial correlations within these datasets. This methodology provides the basis to investigate drought propagation from meteorological to hydro(geo)logical drought without the need to fit distributions for each of the variables of interest.

3.3.3 Drought Thresholds

Drought threshold classifications used throughout this thesis are based on the original drought classifications for the SPI defined by McKee et al., 1993 (Table 3.5). These are used for all the standardised drought indicators throughout this thesis (SPI, SPEI, np-SPI, SSI, SGI and SRI). Figure 3.9 shows how droughts are characterised based on the drought thresholds and onset, peak severity, duration and termination. Drought onset occurs when the SPI reaches a value of -1 or less. Peak severity is the minimum SPI value identified in a drought sequence, event termination occurs when the SPI is continuously positive and reaches a value of 0 or more, drought duration is the number of months SPI values are between -1 and 0.

Table 3.5: SPI classifications

SPI Value	Classification
2.00 or more	Extremely Wet
1.50 to 1.99	Severely Wet
1.00 to 1.49	Moderately Wet
0.99 to -0.99	Near Normal
-1.00 to -1.49	Moderate Drought
-1.50 to -1.99	Severe Drought
-2.00 or less	Extreme Drought

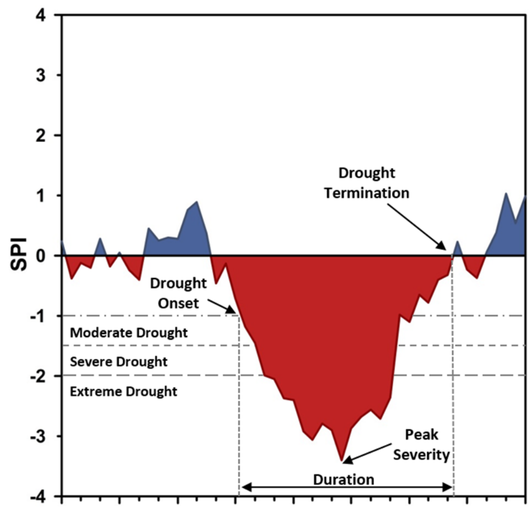

Figure 3.11: Drought classifications and characteristics

3.4 Summary

This chapter has introduced STR with outlines of the climate, hydrology and the STW water resource system, providing the environmental context for the work presented in this thesis. A comprehensive dataset that encompasses climatological, hydro(geo)logical and water resource variables has been constructed and complied for use in the following the chapters using the methods outlined above. Whilst this thesis capitalises on secondary data, the collation and processing of these datasets was a substantial task. This is particularly the case in the sourcing, digitising and transcription of the reservoir level data. The wealth of historical climate data available in the UK allows the construction of several long-series rainfall records to reconstruct historical meteorological droughts within the STR, whilst some of these series pre-exist, for this research each was reanalysed, and some corrected and revised e.g. Rhayader. Whilst the combination of the climatological data with the surface and groundwater datasets enables the assessment of multiple drought types to provide a greater understanding of drought propagation and individual drought structures across the STR.

Chapter 4

Meteorological Drought in the Severn Trent Region

This chapter presents the characterisation of historical meteorological droughts across the STR from 1858-2012 and investigates the impact of the inclusion of long climate data in water resources modelling.

Chapter 4 presents the work undertaken to address objectives one and two of this thesis; (1) *to reconstruct and examine historic meteorological droughts from 1858 onwards and to apply a drought reconstruction in a water resources yield assessment to evaluate historic drought severity, and (2) investigate the spatial and temporal coherence of meteorological drought using multiple sites across the Severn Trent Region to examine spatial and temporal variability of drought and how this would impact water resources management*.

This chapter is divided into five sections, 4.1 presents the results of distribution fitting for the SPI and SPEI and comparison between these indices, 4.2 provides a preliminary analysis of the spatial variability in drought characteristics across the STR as published in the *Proceedings of the International Association of Hydrological Sciences* (Lennard et al., 2015). Section 4.3 details the incidence of major droughts in the STR from 1858-2012, 4.4 presents the application of a meteorological drought reconstruction for a single water resource zone in the STR; this has been published in the journal *Hydrological Research* (Lennard et al., 2016). Section 4.5 examines the sub-regionalisation of rainfall and meteorological drought and explores the temporal variability of key droughts across the STR.

4.1 Meteorological Drought Indices

Meteorological drought indices are widely used, with a number of different indices available (see section 2.1). Approaches to the computation of the SPI/SPEI are widely discussed (Guttmann, 1999; Lloyd-Hughes and Saunders, 2002; Giddings et al., 2005; Vicente-Serrano et al., 2010; Stagge et al., 2015b) with a particular focus on identifying best-fit theoretical distributions, a key component in the computation of the SPI/SPEI.

4.1.1 Assessing SPI/SPEI Distribution Fitting

Accumulated rainfall and climatic water balance data at 1-, 3-, 6-, 9- and 12-months are fitted to a number of candidate distributions (section 3.3.1). Whilst Stagge et al. (2015b) recommend the use of a single distribution for regional scale studies, Sienz et al. (2012) suggest the use of a 'multi-distribution' approach that applies the best fit distribution for each rainfall/climatic water balance dataset. However, this does not allow for the comparison of SPI/SPEI values between sites; variation in SPI/SPEI values between sites may result from the selection of different probability distributions used rather than differences in the rainfall data. Prior to applying any single fitted distribution to each/all sites, the suitability of the common fitting approaches are assessed. All the distribution fitting results are presented for the eight long-series rainfall and climatic water balance datasets for brevity, but the same method is applied for all rainfall and climatic water balance datasets used in this thesis.

SPI

At the shortest accumulation period of 1-month, Weibull and Gumbel distributions provide the best fit across all stations (Table 4.1). Results for the SPI show that the gamma distribution accounts for the *highest* proportion (65%) of the best fit between 3- and 12-month accumulation periods (Table 4.1, Figure 4.1). As the accumulation period increases across all stations the number of best fit distributions also increases. 1- and 3-month periods show best fit to two distributions across all stations; Gumbel and Weibull (1-month) and Gumbel and gamma (3-months). At 6- and 12-months three distributions account for best fit across all stations, gamma, normal and log-normal (6-months) and gamma, normal and logistic (12-months). The 9-month accumulation period across all stations identifies four best fit distributions, gamma, normal, logistic and log-normal. These findings are similar to those of Stagge et al. (2015b). As the gamma distribution is most frequently the best fit distribution it is used to calculate the SPI throughout this thesis, an approach also suggested by Stagge et al. (2015b) for regional SPI studies in Europe.

Table 4.1: Candidate distributions for SPI at 1-, 3-, 6-. 9- and 12-month accumulation periods (1900-2012)

	Accumulation Periods				
Site	**1-month**	**3-month**	**6-month**	**9-month**	**12-month**
Rhayader	Gumbel	Gumbel	Gamma	Gamma	Gamma
Chatsworth	Gumbel	Gamma	Gamma	Logistic	Logistic
Weston Park	Gumbel	Gamma	Gamma	Gamma	Gamma
Rugby	Weibull	Gamma	Normal	Normal	Normal
Wall Grange	Weibull	Gamma	Gamma	Normal	Gamma
Nanpantan	Weibull	Gamma	Gamma	Gamma	Normal
Oakly Park	Weibull	Gamma	Gamma	Logistic	Logistic
Nottingham	Gumbel	Gamma	Log-normal	Log-normal	Gamma

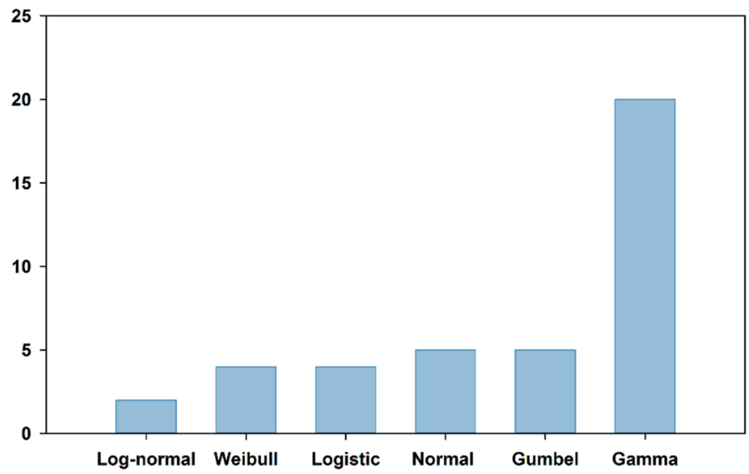

Figure 4.1: Proportion of best fit distributions for SPI computation

SPEI

Of the three distributions tested in the fitting of the climatic water balance, two distributions account for the best fit at all timescales and sites (Table 4.2, Figure 42). The GEV distribution accounts for the highest proportion (60%), whilst PE3 accounts for the remaining 40%. At 1- and 12-month accumulation periods the PE3 distribution is the best fit at the majority of sites. At 3-, 6- and 9-months the GEV distribution is the best fit. As with the SPI distributions these findings are broadly similar to Stagge et al. (2015b) with the GEV distribution the dominant best fit distribution across the UK. The GEV distribution is used in the calculation of the SPEI in this thesis as it accounts for the highest proportion of best fit distributions across the STR.

Table 4.2: Candidate distributions for SPEI at 1-, 3-, 6-. 9- and 12-month accumulation periods (1900-2012)

	Accumulation Periods				
Site	**1-month**	**3-month**	**6-month**	**9-month**	**12-month**
Rhayader	PE3	GEV	GEV	PE3	PE3
Chatsworth	PE3	GEV	GEV	GEV	PE3
Weston Park	GEV	GEV	GEV	GEV	GEV
Rugby	PE3	GEV	GEV	GEV	PE3
Wall Grange	PE3	GEV	GEV	GEV	GEV
Nanpantan	PE3	GEV	GEV	PE3	GEV
Oakly Park	GEV	GEV	GEV	GEV	PE3
Nottingham	PE3	PE3	GEV	PE3	PE3

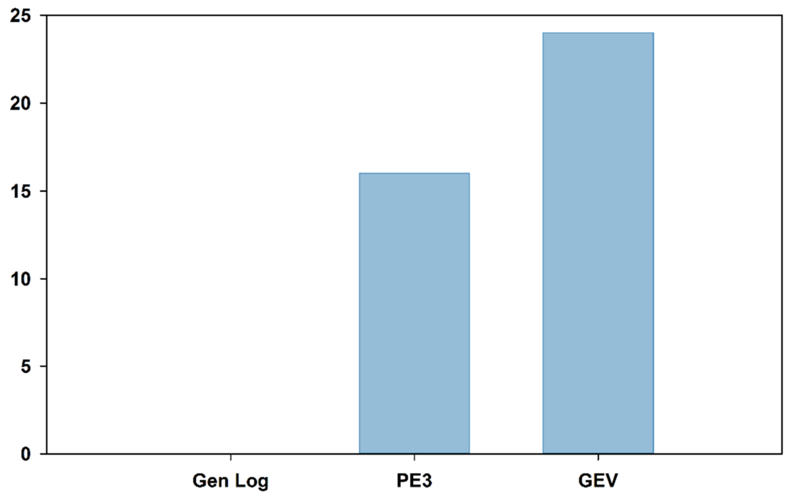

Figure 4.2: Proportion of best fit distributions for SPI computation

4.1.2 Comparison of the SPI and SPEI

The SPEI is a progression on the SPI that includes an evapotranspiration component to represent the role of temperature in the formation of meteorological drought, which is valuable in investigating potential impacts of current and future temperature variability (Vincent-Serrano et al., 2010). The SPEI is included in this thesis to investigate the role of evapotranspiration data in meteorological drought characterisation in the STR. The SPI and SPEI are compared using Pearson's Correlation Coefficient for each timescale of interest (1-, 3-, 6-, 9- and 12-months). The SPI and SPEI produce consistent results, correlation coefficients range from 0.99 to 0.96 (Table 4.3). Analysis of the timing of drought onset, termination and duration between the SPI and SPEI results for each site identifies little or no difference. The ranked severity of each drought event is consistent, for example, at Chatsworth the 1921-22 drought is the most severe event between 1900-2012 using both the SPEI and SPI (Figure 4.3).

Throughout this chapter meteorological drought characterisation is presented using only the SPI. Whilst the SPEI is a valuable addition to the suite of meteorological drought indicators available, within this thesis it appears to add little additional information in meteorological drought characterisation; the SPI is a simpler index with fewer assumptions (particularly with the uncertainty associated with evapotranspiration estimates) and is therefore preferable in this thesis.

Table 4.3: Pearson correlation coefficient between SPI and SPEI all values are significant at 95% level

Site	1-month	3-month	6-month	9-month	12-month
Rhayader	0.99	0.99	0.98	0.98	0.98
Chatsworth	0.98	0.98	0.98	0.97	0.97
Weston Park	0.98	0.98	0.98	0.98	0.98
Rugby	0.97	0.97	0.97	0.96	0.96
Wall Grange	0.98	0.98	0.98	0.97	0.97
Nanpantan	0.98	0.98	0.97	0.97	0.96
Oakly Park	0.98	0.98	0.98	0.97	0.97
Nottingham	0.98	0.98	0.97	0.96	0.96

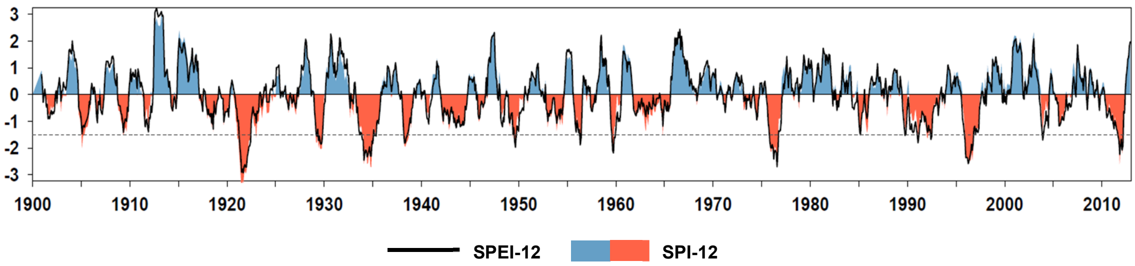

Figure 4.3: SPI and SPEI at 12-month timescale for Chatsworth

4.2 "Analysis of Drought Characteristics for Improved Understanding of a Water Resource System"

(Lennard, A.T., Macdonald, N., Hooke, J., 2014. Analysis of drought characteristics for improved understanding of a water resource system, in: Castellarin, A., Ceola, S., Toth, E., Montanari, A. (Eds.), Evolving Water Resources Systems: Understanding, Predicting and Managing Water–Society Interactions Proceedings of ICWRS2014, Bologna, Italy, June 2014 (IAHS Publ. 364, 2014). IAHS, pp. 404–409. doi:10.5194/piahs-364-404-2014 404)

The peer reviewed paper is reproduced below representing section 4.2 of the thesis, the only modifications being that the figure and table numbers run concurrent to the thesis, and uses rainfall data from 14 sites, rather than the 15 outlined in Chapter 3; after the publication of this work an additional rainfall record at Clywedog in the Welsh uplands was added to provide greater coverage of this area of the STR (Figure 3.5).

4.2.1 Abstract

Droughts are a reoccurring feature of the UK climate; recent drought events (2004–2006 and 2010–2012) have highlighted the UK's continued vulnerability to this hazard. There is a need for further understanding of extreme events, particularly from a water resource perspective. A number of drought indices are available, which can help to improve our understanding of drought characteristics such as frequency, severity and duration. However, at present little of this is applied to water resource management in the water supply sector. Improved understanding of drought characteristics using indices can inform water resource management plans and enhance future drought resilience. This study applies the standardised precipitation index (SPI) to a series of rainfall records (1962–2012) across the water supply region of a single utility provider (STW). Key droughts within this period are analysed to develop an understanding of the meteorological characteristics that lead to, exist during and terminate drought events. The results of this analysis highlight how drought

severity and duration can vary across a small-scale water supply region, indicating that the spatial coherence of drought events cannot be assumed.

4.2.2 Introduction

Droughts are complex natural hazards with multifaceted effects that can cause significant socio- economic and environmental impacts. As a recurrent feature of the European climate, there have been several drought events during the 20th Century (Lloyd-Hughes and Saunders 2002). It is estimated that the cost of drought in Europe in the past 30 years was €100 billon (EC 2007). Recent drought events (2004–2006 and 2010–2012) have highlighted the UK's continued vulnerability to this hazard. Recent events identify the need for continued drought research across the UK. Brown et al. (2010) identify an increased understanding of extreme events (droughts and flooding) as a key research priority within the UK water sector.

UK drought research is predominantly focused on climate models and prediction, with little use of drought indices for event characterisation, ignoring the wealth of long climate data series available (Todd et al. 2013). Past research is focused at European or national scales rather than at a regional scale, with large-scale studies often failing to capture the spatial variability that a smaller, regional study could provide (Hannaford et al. 2011). Regional-scale studies are more beneficial for water resource management, as shown by Phillips and McGregor (1998) and Fowler and Kilsby (2002) who use a regionalised approach to characterise drought events. Panu and Sharma (2002) identified several areas of future research focus within droughts; these included the importance of drought indices and recognition of regional variability. Although, there have been several drought studies in the UK, few of these have applied the Standardised Precipitation Index (SPI). The SPI developed by McKee et al. (1993), is a widely applied meteorological drought index that quantifies precipitation deficits. At present, the SPI is underutilised for drought management planning and monitoring in the UK by both government agencies and the water supply sector. In this study, precipitation data from locations across a single water sector supply region are analysed using the SPI to determine drought structures, with the aim of improving understanding of drought characteristics for water resource management.

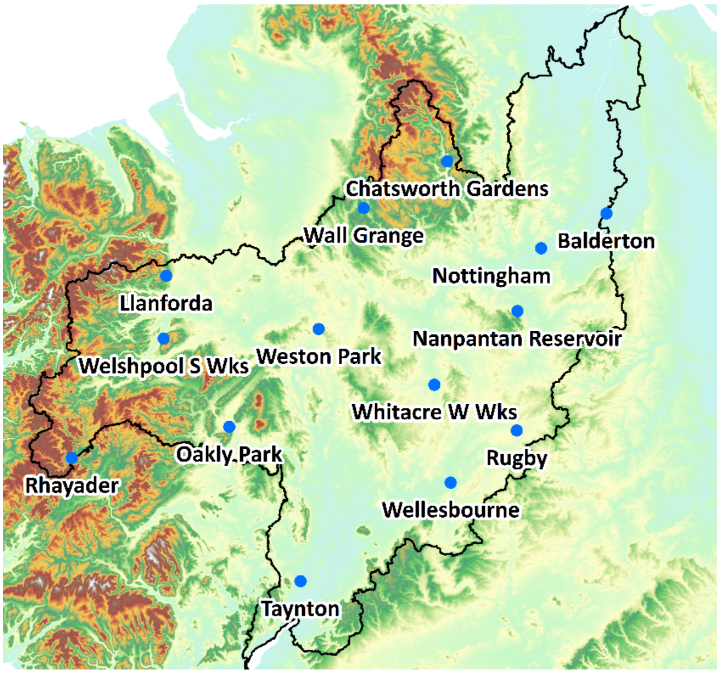

Figure 4.4: Map of 14 rain gauges used in drought characterisation

Study Area

The Severn Trent Water supply region (Figure 4.4) is approximately 21 000 km^2 spanning central England and mid-Wales. The study area includes a variety of landscapes with uplands over 400 m a.s.l. in the north and west; the central plateau region is at between 100 to 250 m a.s.l. and the south and east of the region has lower lying relief. Considerable variation in rainfall exists across the region, ranging from 1800 mm in the Welsh uplands to 650 mm in the southeast of the area (Met Office, 2013). Severn Trent Water supply approximately 7.4 million people in the region; supplies are sourced from reservoirs, river abstractions and groundwater, with each source contributing approximately 33% to the total supply.

4.2.3 Methods and Materials

Data

Daily precipitation data were collected from 14 sites (Figure 4.4) across the study region from 1962– 2012, of which seven series are available for the period 1900–2012 providing a longer-temporal context. However, these long series are not within the scope of this paper. The time period 1962– 2012 was selected for two reasons: (i) The period provides a sufficient record length to ensure meaningful SPI calculations; and (ii) the start of the 1960s witnessed an increase in precipitation recording across the region. The rain gauges selected are at a variety of altitudes (17–268 m a.s.l) reflecting the varying climatological conditions of the study area. Precipitation data were obtained from the British Atmospheric Data Centre (www.badc.nerc.ac.uk). The site selection process included checks for percentage of data missing (sites with more than 20% of data missing were rejected) and identification of suitable weather stations to provide missing data. Gaps in the records were filled using linear regression techniques with data from additional suitable nearby weather stations (all weather stations used for missing data were within 10 km of the selected sites), a detailed description of this method can be found in Macdonald et al. (2008); these were checked for homogeneity, trend and randomness.

Standardised precipitation index

The standardised precipitation index (SPI) is a commonly used meteorological drought index to quantify rainfall deficits based on the probability of precipitation for multiple time scales. Commonly used time scales are 1-, 3-, 6-, 12- and 24-month. These time scales are selected to reflect the impact of drought on various water resources; e.g. soil moisture responds at a faster rate to rainfall deficits than groundwater. SPI values are a dimensionless unit usually ranging from 2 to –2 (see Lloyd-Hughes and Saunders (2002) for a detailed review of the SPI). SPI values and corresponding drought classifications are shown in Table 4.4. A drought event is assumed to occur when the SPI value is smaller or equals –1.00; drought termination is assumed when the SPI exceeds or equals 0. The standardised nature

Table 4.4: SPI classifications

SPI Value	Classification
2.00 or more	Extremely Wet
1.50 to 1.99	Severely Wet
1.00 to 1.49	Moderately Wet
0.99 to -0.99	Near Normal
-1.00 to -1.49	Moderate Drought
-1.50 to -1.99	Severe Drought
-2.00 or less	Extreme Drought

of the SPI allows for the comparison of drought conditions at different locations. Calculations are based on long-term rainfall records for a chosen time period. The SPI calculation was applied to rainfall data for each of the 14 sites at a 12 month timescale for the period 1962–2012. This study focuses on the SPI-12 month scale as this is appropriate when considering the impact of drought on surface waters (Mishra and Singh 2010).

4.2.4 Results and Discussion

The SPI series for each site from 1962–2012 are presented in Fig. 4.6. Three multi-year droughts can be identified: 1975–1976, 1995–1996 and 2010–2012. These drought events were investigated further to determine the key characteristics in their formation.

Drought characteristics

1975–1976

Drought onset varies from September in the centre and north of the STR at Chatsworth, Oakly Park, Welshpool and Whitacre to December 1975 at Rhayader on the western edge of the region. Drought duration varies across the region, from 16 month (Rugby, Nanpantan, Balderton and Wellesbourne) to 20 months (Rhayader and Llanforda). Peak severity occurred in July (Nanpantan, Taynton, Wellesbourne and Whitacre) and August 1976 at all remaining sites; from September 1976 drought conditions become less extreme. Termination of drought conditions is also variable across the region (Figure 4.5a). Across much of the region drought termination was reached by February 1977; however, at Wall Grange and Rhayader termination occurs in April and July 1977 respectively. The drought was classified as extreme across the region, with peak severities ranging from –2.59 to –3.42.

1995–1997

Onset varied across the region from August 1995 (Whitacre) to February 1996 (Rhayader); by February 1996 all sites with the exception of Taynton are in drought. Drought onset does not occur at Taynton until December 1996. Event duration ranges from 12 months (Taynton) to 31 months (Nottingham) (Fig. 4.5b). The drought continued through until 1997; by May 1997 the severity of the drought had begun to reduce at all sites. Rainfall had returned to “normal” conditions by January 1998 with the exception of Nottingham, where the drought terminates in April 1998. Peak severity ranged from –1.58 (Taynton) to –2.96 (Chatsworth).

2010–2012

Drought onset was highly variable across the region ranging from June 2010 (Weston Park) to August 2011 (Rugby, Nottingham and Balderton) (Figure 4.5c). Seven sites entered drought conditions in 2010 (Rhayader, Wall Grange, Oakly Park, Llanforda, Welshpool and Whitacre) these sites are predominantly in the west and north of the STR. At Chatsworth, Rugby, Nanpantan, Nottingham, Balderton, Taynton and Wellesbourne onset occurs between March and August 2011. Drought duration was also highly variable across the region, ranging from 8 months (Balderton) to 26 months (Weston Park). Peak severity is reached at all sites in October and November 2011; ranging from -1.39 (Rhayder) to -3.38 (Whitacre) By March 2012 the drought becomes less severe across the region. Event termination ranges from June (Chatsworth, Rugby, Wall Grange, Nanpantan, Nottingham, Balderton and Taynton) to November (Rhayader) 2012.

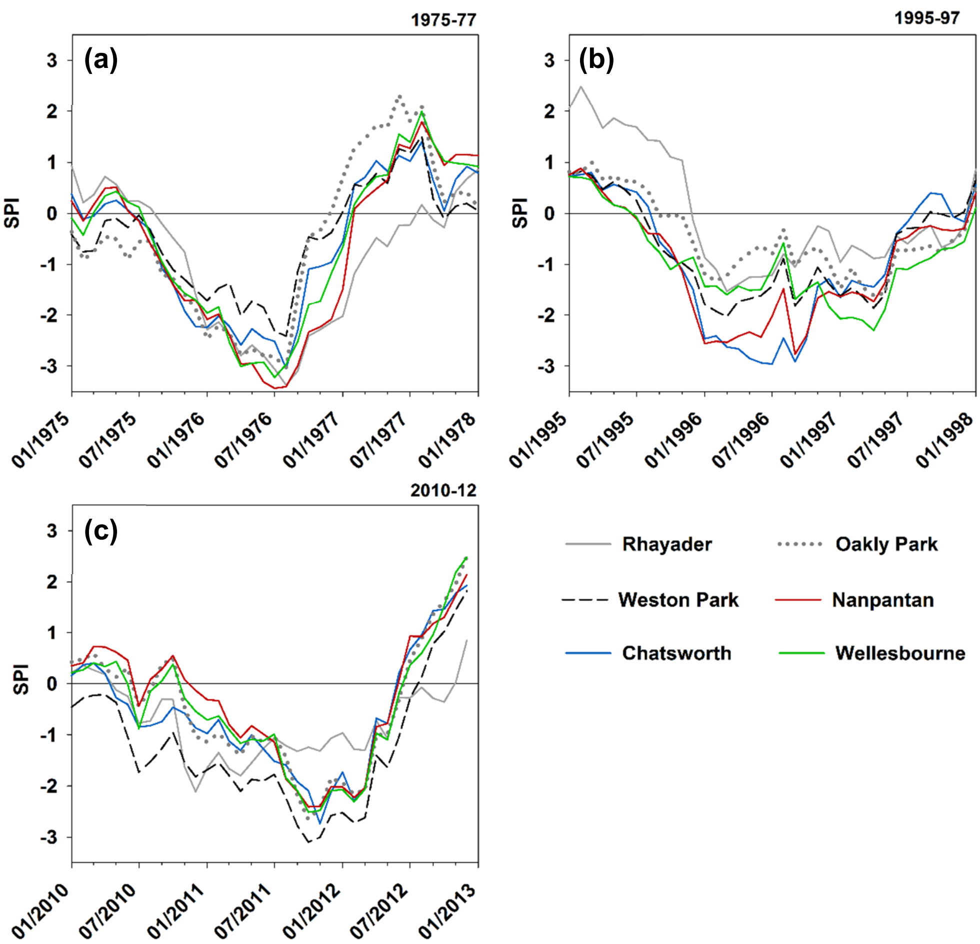

Figure 4.5: SPI-12 series for six sites for drought events (a)1975-77, (b) 1995-97, (c) 2010-12

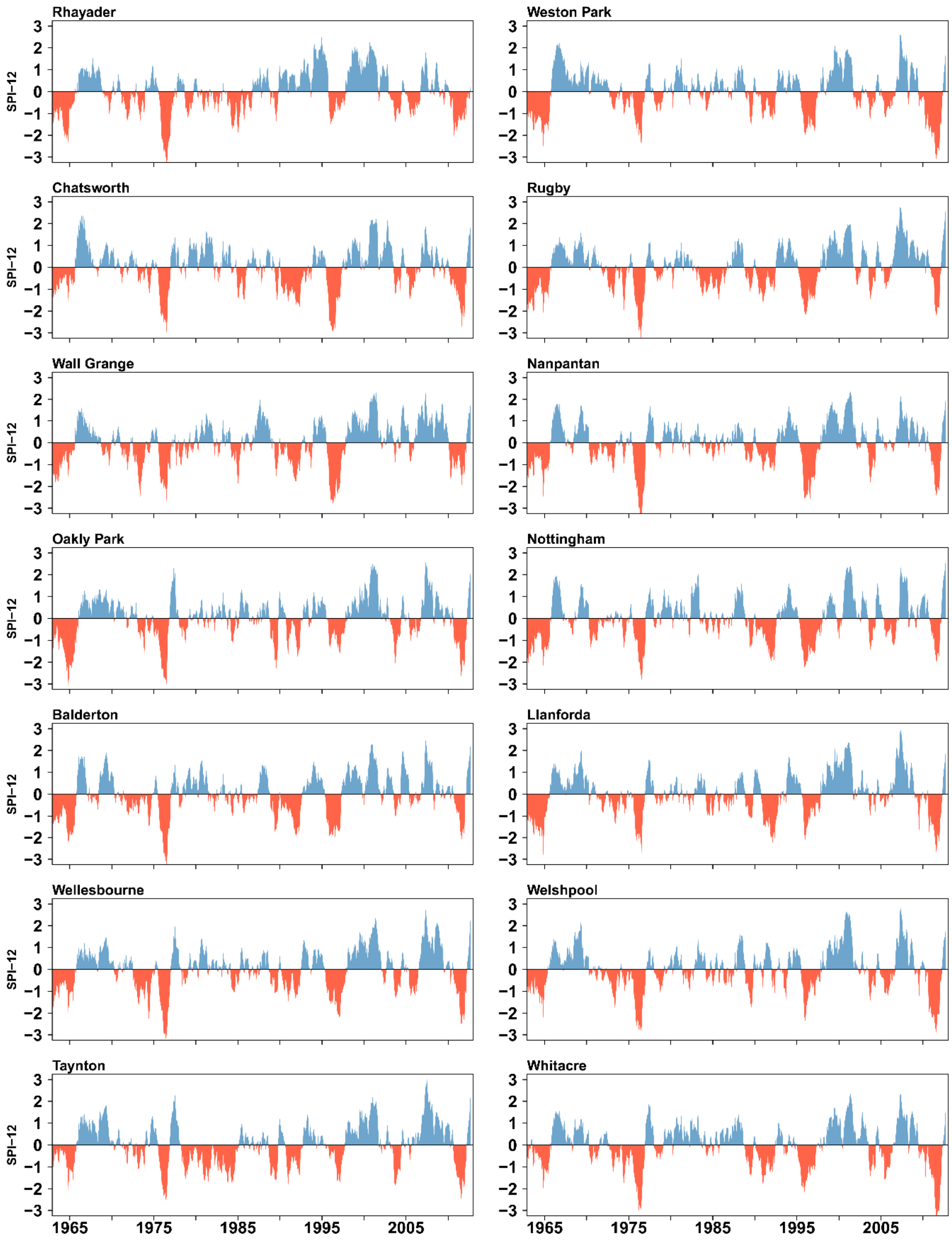

Figure 4.6: SPI-12 reconstruction 1962-2012

Spatial variability

Pearson's correlation coefficient is used to identify the significance of relationships between the SPI values. There are significant correlations between all the sites at the 0.01 level (Figure 4.7); this is expected due to the close proximity of the sites in the study area. The highest correlation coefficient is 0.91 between Nanpantan and Nottingham, the lowest 0.52 between Nottingham and Rhayader. The variation in inter-site correlation is a function of distance between the sites. The relationship between site Rhayader and all other sites is consistently the weakest; the largest correlation coefficient is 0.75 between Rhayader and Welshpool. The weaker relationships between Rhayader and other sites suggest there is a distinct climatology for the site and surrounding upland areas in the west of the supply region. Examination of the correlation coefficient analysis suggests there are divisions within the drought climatology of the region, with sites in the west (Rhayader, Welshpool, Llanforda, Oakly Park, Taynton) showing strong inter-site relationships, whilst the same is also observed for sites in the east of the region (Nottingham, Balderton, Nanpantan, Rugby, Wellesbourne). However, these results are preliminary, with further analysis required to fully establish whether there are distinct sub-regional drought climatologies.

	Balderton	Nottingham	Nanpantan	Rugby	Wellesbourne	Chatsworth	Whitacre	Wall.Grange	Weston.Park	Taynton	Oakly.Park	Llanforda	Welshpool	Rhayader
Balderton	1.00													
Nottingham	0.90	1.00												
Nanpantan	0.91	0.90	1.00											
Rugby	0.86	0.81	0.89	1.00										
Wellesbourne	0.82	0.78	0.89	0.90	1.00									
Chatsworth	0.82	0.81	0.85	0.78	0.78	1.00								
Whitacre	0.79	0.79	0.86	0.82	0.89	0.83	1.00							
Wall.Grange	0.77	0.71	0.78	0.78	0.77	0.81	0.72	1.00						
Weston.Park	0.79	0.75	0.83	0.82	0.86	0.79	0.87	0.76	1.00					
Taynton	0.68	0.61	0.75	0.78	0.79	0.58	0.69	0.59	0.73	1.00				
Oakly.Park	0.78	0.75	0.81	0.79	0.86	0.72	0.82	0.69	0.87	0.83	1.00			
Llanforda	0.80	0.74	0.83	0.80	0.82	0.79	0.79	0.77	0.83	0.76	0.86	1.00		
Welshpool	0.76	0.71	0.81	0.78	0.83	0.74	0.80	0.72	0.83	0.72	0.84	0.87	1.00	
Rhayader	0.58	0.52	0.66	0.63	0.64	0.59	0.55	0.67	0.65	0.62	0.67	0.70	0.75	1.00

Figure 4.7: Pearson's correlation coefficient for SPI-12

Although there is considerable similarity between sites, there is variability in the drought characteristics between sites, with implications for water resource management, particularly drought duration and magnitude. The variability may alter recovery times of reservoirs, e.g. during the 1975–1976 drought, Rhayader located next to a strategically important reservoir system lagged 8 months behind drought termination at Oakly Park, shown in Figure 4.5. This indicates that spatial coherence of drought events cannot be assumed, particularly when focusing on the implications of drought on water resources.

Implications for water resource management

Reconstructing drought series for past events improves our understanding of drought characteristics for a region, providing improved understanding of drought characteristics, propagation of drought through a water resource system and possible insights into the impact of climate change on future droughts. However, analysis of meteorological drought characteristics is insufficient to gain a full understanding of drought characteristics and the implications for water resource management. It would also be beneficial to utilise long series, particularly precipitation data (>100 years) in the UK, to place recent events into a longer term context (Marsh et al. 2007). Future work will include analysis of long precipitation series. It is necessary to consider stream flow, groundwater and reservoir data to develop a more complete understanding of future drought risks, with few studies having previously considered all available data sources.

4.2.5 Conclusion

Recent drought events in the UK have highlighted the need for continued research, including the impact of hydrological extremes within the water resource and management sector. The SPI is rarely been applied in the UK, with previous research often focused on modelling approaches, ignoring the use of drought indices and long data series available for analysis. This study applies the SPI across 14 sites in a single UK water resource region to characterise drought events from 1962–2012. During this period, three multi-year droughts were identified: 1975–1976, 1995–1997 and 2010–2012. The characteristics of these events have been analysed to investigate spatial variability across the water supply region. Event onset, duration and termination are particularly variable. Understanding the features of past key drought events may be used to inform future management decisions. However, the use of longer precipitation records (>100 years) that contain periods of drought during the early 1900s, 1920s and 1930s would provide important long- temporal context in terms of drought severity, frequency and duration. In order to explore this further section 4.3 examines meteorological droughts in the STR starting from 1858.

4.3 A High Resolution Reconstruction of Historic Meteorological Droughts

A series of long precipitation series (the earliest starting in 1858) are used to generate long SPI drought series (Figure 4.8), these are then examined to characterise the most notable drought events. The earliest drought identified (1863-65) can only be characterised using three rainfall records- Rhayader, Chatsworth and Weston Park, with subsequent droughts investigated using further records as each additional series become available (Figure 3.5a, page). To enable a comparison between rainfall records the SPI is calculated for consistent time periods (1858-2012 three sites; 1887-2010 five sites, and 1900-2012 eight sites), for example, the 1862-65 drought is characterised using the three rainfall series from 1858-2012, whilst the 1920-21 drought is characterised using the eight series from 1900-2012.

Drought events are identified with the SPI using drought thresholds (explained in section 3.3.3); drought onset occurs at ≤-1 and termination at ≥ 0. Drought duration is measured as the months between drought onset and termination, with peak severity/intensity the month with the lowest SPI-value within a drought event. This chapter is focused on the incidence of major droughts in the STR that are 10 months or more in duration at the majority of sites based on an SPI-12 reconstruction. There are a number of shorter drought events identified in the reconstruction, however, these are excluded from the analysis at this stage as the impact of these events on surface and groundwater sources is likely to be less significant. To reflect drought impacts on surface water and groundwater resources results are presented using both the SPI-6 and SPI-12. Whilst a number of studies (Vicente-Serrano & Lopez-Moreno, 2005; Vicente-Serrano, 2006; Haslinger et al., 2014) have suggested alternative SPI accumulation periods that better represent hydro(geo)logical drought, the SPI-6 and SPI-12 have been selected for the initial identification of the most notable meteorological droughts since 1858. The individual historic drought characteristics detailed within this section are then further examined within the context of water resource management in the Severn-Trent region, examining the implications of the historical drought structures on water resource management planning.

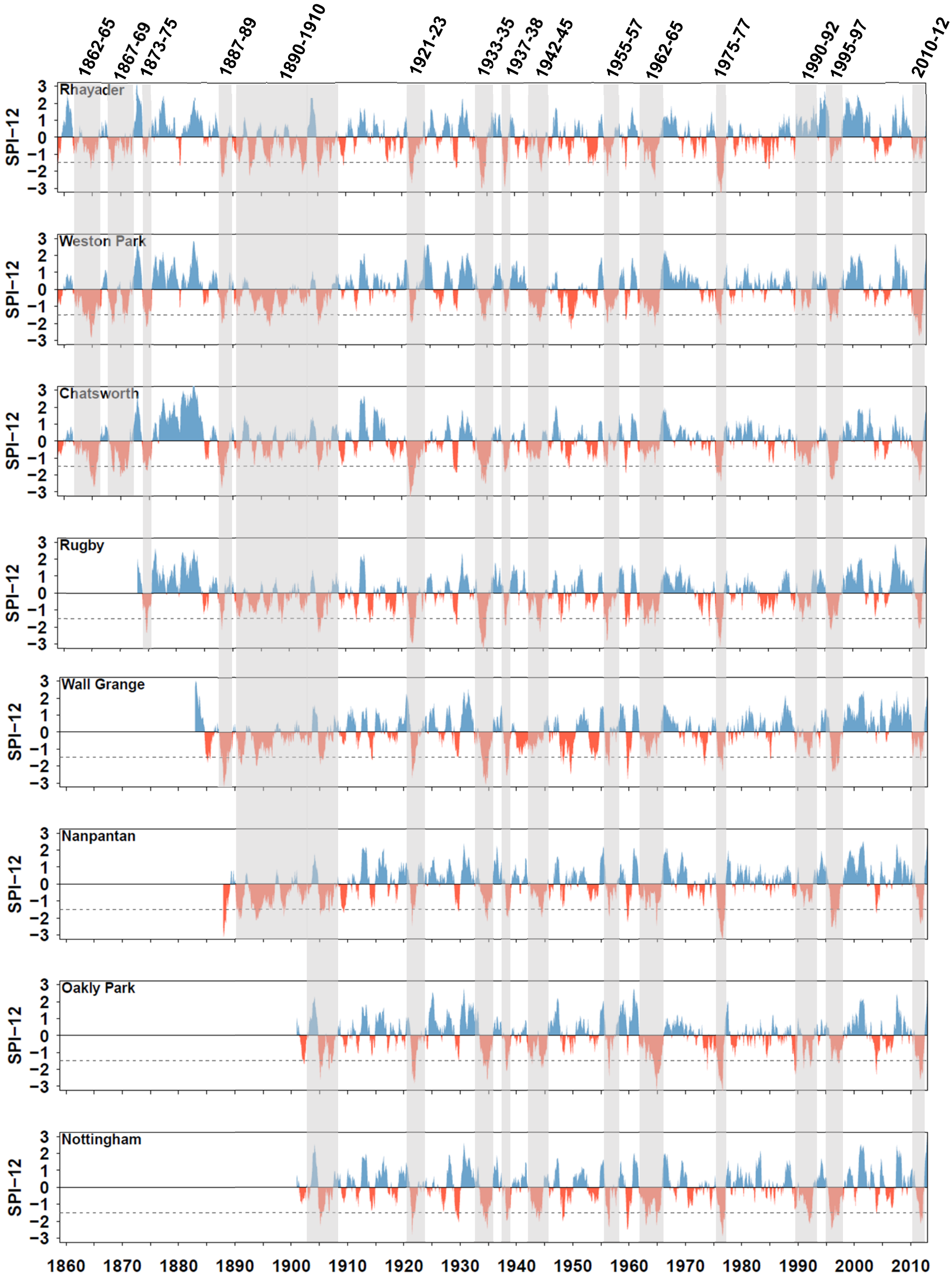

Figure 4.8: SPI-12 for each long series rainfall record, dashed line indicates moderate drought (-1.5)

4.3.1 1862-66 Drought

Three rainfall records Rhayader, Weston Park and Chatsworth are available for the region to identify and characterise the earliest droughts examined in this thesis. The period 1862-76 appears to be drought rich (Figure 4.9). Four drought events in this period have been identified; (1) 1862-66, (2) 1868-69, (3) 1870-72 and (4) 1874-76. The longest and most severe drought event is 1862-66, which is particularly prominent at Weston Park and Chatsworth. The 1868-71 and 1873-76 drought events are punctuated by a wet period in 1872 with SPI values exceeding 2 at all sites.

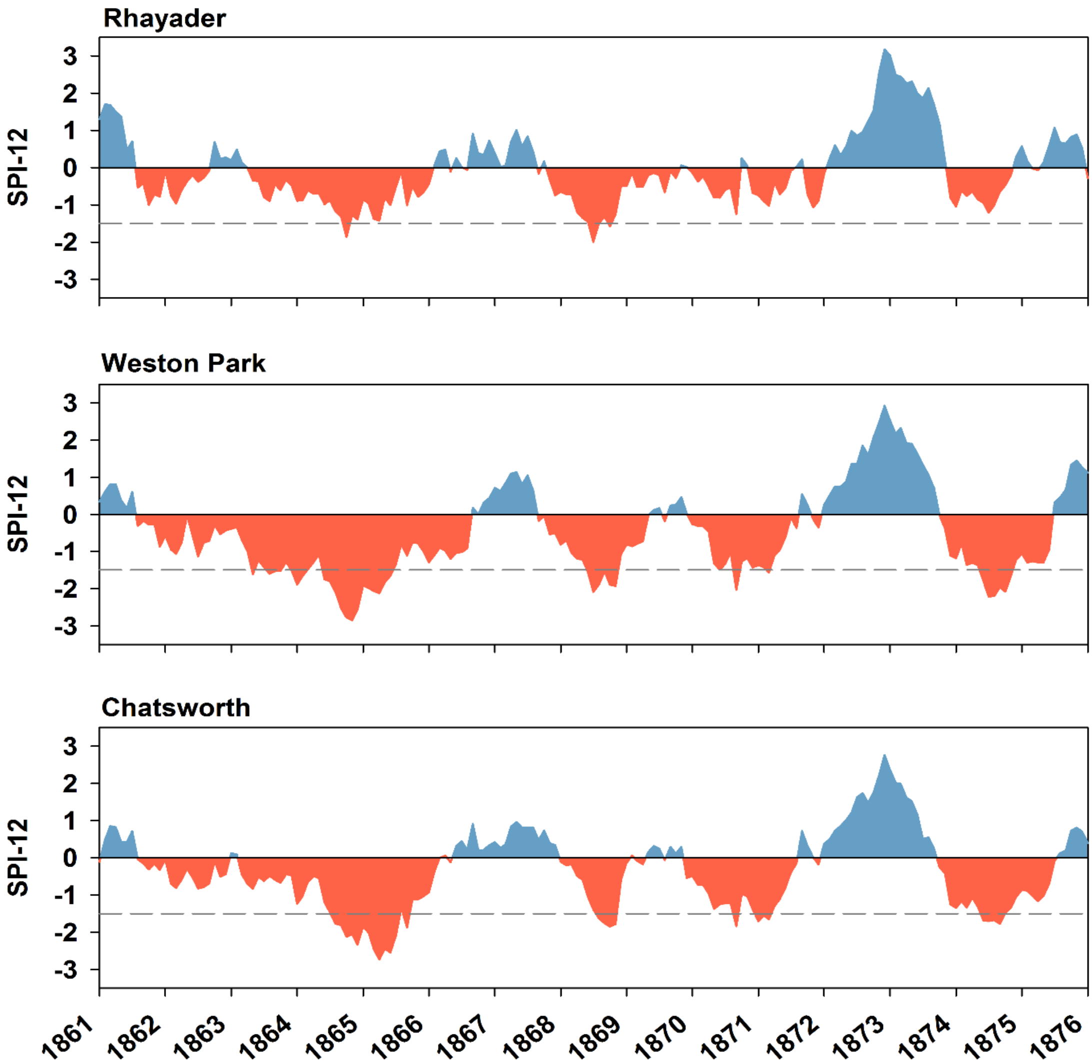

Figure 4.9: SPI-12 for drought rich 1861-75, dashed line indicates moderate drought (-1.5 SPI)

The first drought identified in the record is 1862-66 (Fig. 4.10), using the SPI-6 (Figure 4.10a) three phases to the drought are identified. The first is of short duration drought between January and May 1862 at Weston Park and Chatsworth (five months) and a four month event between February and May at Rhayader. The second drought phase at Weston Park is identified from February 1863 until August 1866 with a total drought duration of 43 months. At both Chatsworth and Rhayader there are two drought phases during the same timeframe in 1863 and 1864-1865. At Rhayader, the first phase occurs from April 1863 to August 1863 lasting for five months. At Chatsworth, the first phase is occurs from April 1864 to September 1865 lasting seven months. At both Rhayader and Chatsworth, the second phase occurs from April 1864 to September 1865 with a duration of 18 months.

Analysis of drought characteristics using SPI-12 (Figure 4.10b) results in increased drought durations, with smaller drought events pooled or amalgamated. At Weston Park this results in a drought duration of 54 months from March 1862 until August 1866. The peak drought severity at Weston Park is -2.85 in November 1864, this is the lowest SPI value in the 1858-2012 drought reconstruction for this site. The 12-month total rainfall accumulation from December 1863 to November 1864 accounts for the lowest 12-month rainfall total at Weston Park from 1858-2012 with a total of 408mm. October 1864 accounts of the second lowest SPI value for Weston Park at -2.78. At Chatsworth, drought duration is 29 months with event onset in January 1864 and termination in June 1866. Peak drought severity occurs in April 1865 at -2.75, this ranks as the 6th lowest SPI value for Chatsworth from 1858-2012 with a total 477mm of rainfall accumulated over the 12-months from May 1864 to April 1865. June 1865 is ranked as the 7th lowest SPI value for Chatsworth. This event is shorter and less severe at Rhayader, drought duration is 18 months with a peak severity of -1.39.

The severity and duration of the drought could be exacerbated by snow fall, which is generally under-recorded as a result of rain gauge under-catch (Forland and Hanssen-Bauer, 2000). The general weather descriptions from Symons' British Rainfall Report 1865 (Symons, 1866) describes significant snowfall across Britain in January, February and March 1865.

4.3.2 1867-69 and 1870-71 Droughts

Using the SPI-6 (Figure 4.11a), drought onset at Rhayader and Weston Park is in November 1867 and terminating in December 1868 with a total duration of 14 months. At Chatsworth, the drought is shorter with an 11-month duration, onset occurs in January 1868 and termination in November 1868. Peak drought severity (-1.71) occurs at Rhayader in January 1868, in July 1868 (-2.17) at Weston Park and in November 1868 (-1.72) at Chatsworth. Drought termination is rapid and abrupt at all sites, SPI values increase from <-1.2 to > 0.20 between November 1868 and January 1869 across all sites (Figure 4.11).

Based on the SPI-12 (Figure 4.11b), the characteristics of this event at Rhayader and Weston Park are similar from drought onset to peak severity with both sites reaching peak intensity in July 1868 (-1.99 and -2.09 respectively). However, drought duration at Rhayader is 19 months from April 1868 and terminating in October 1869, at Weston Park duration is 15 months from March 1868 and terminating earlier than Rhayader in May 1869. At Chatsworth drought duration is shorter at nine months with a peak intensity (-1.85) in October 1868.

The onset of the 1870-71 drought is coherent across the three sites, occurring in June 1870, based on SPI-6 results (Figure 4.11a). At Rhayader, peak severity (-2.13) occurs in August before rapid termination by October, this gives a total drought duration of four months. At Weston Park and Chatsworth the drought is longer at 15 months and 13 months respectively, at both sites peak severity occurs in in September 1870 (-2.90 at Weston Park, -2..95 at Chatsworth). At Chatsworth drought termination occurs in July 1871, followed by Weston Park in September 1871. The SPI-12 results (Figure 4.11b) show drought characteristics at Weston Park and Chatsworth are very similar at both sites, onset occurs in May 1870, peak severity in September 1870 terminating in September 1871 with a total event duration of 16 months. Rhayader exhibits different drought characteristics, SPI values reach <-1.00 for one month in September 1870 followed by a second drought phase from March to August 1871.

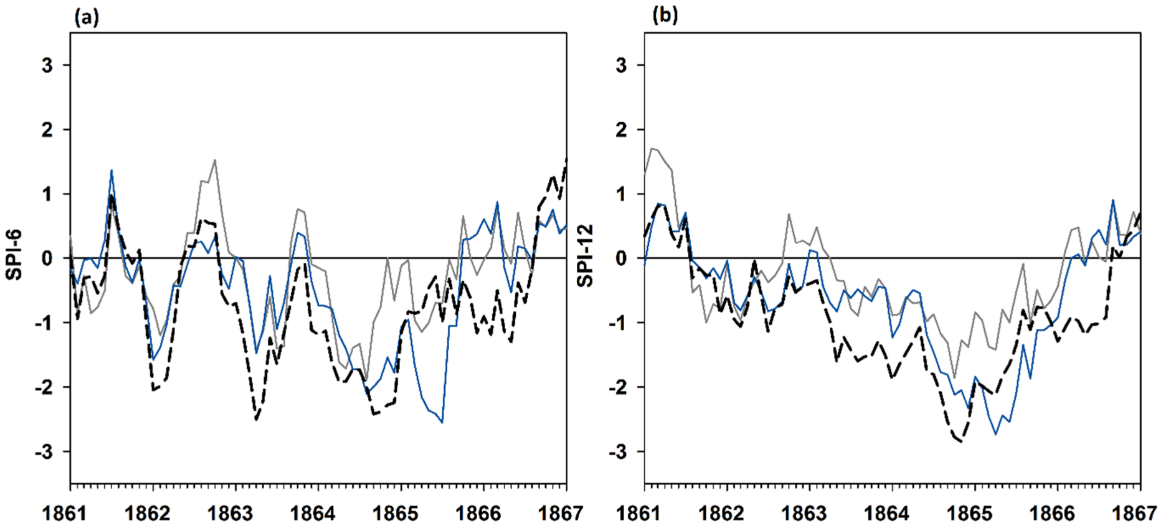

Figure 4.11: (a) SPI-6, (b) SPI-12 for 1862-65 drought

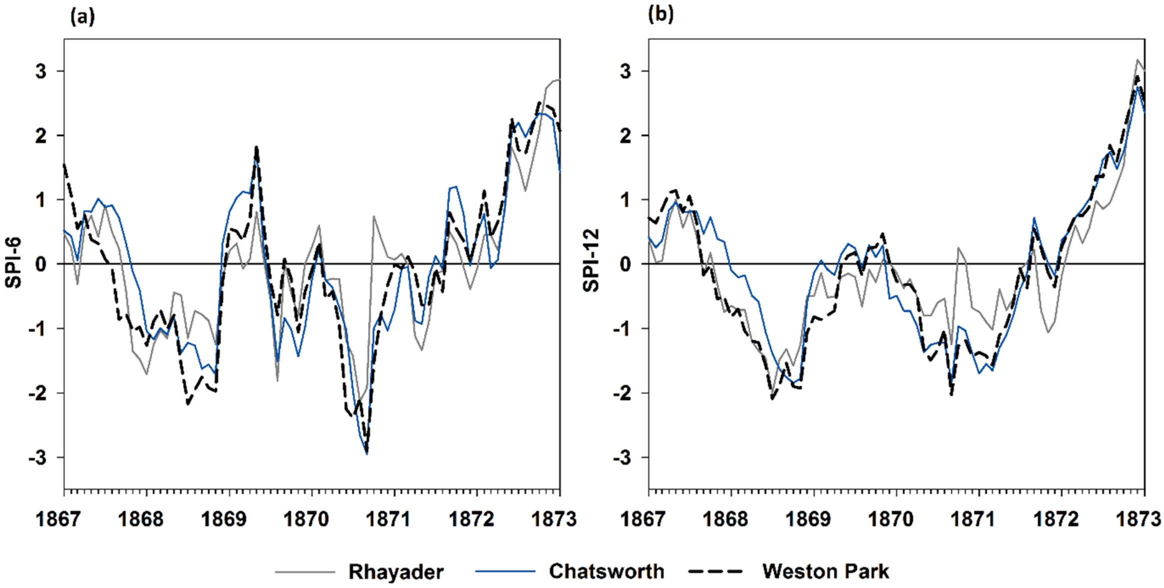

Figure 4.11: (a) SPI-6, (b) SPI-12 for 1867-69 and 1870-71 droughts

4.3.3 1873-75 Drought

The 1873-75 drought (Figure 4.12) is characterised at four sites, Rhayader, Chatsworth, Weston Park and Rugby, with records available for the latter from 1872-2012. Drought onset occurs in December 1873 at Chatsworth, Weston Park and Rugby followed by Rhayader in January 1874, based on SPI-6 and SPI-12 results. Drought duration is shortest at Rhayader, seven months (SPI-6) terminating in August 1874 or 11 months (SPI-12) terminating in November 1874. Based on SPI-6 (Figure 4.12a) this drought has a duration of 13 months at all other sites, ending in December 1874. After this termination point a second phase of low rainfall is initiated with SPI values reaching <-1 for up to 3 months at Chatsworth, Weston Park and Rugby. Based on the 12-month accumulation period, this second dry phase causes the continuation of drought conditions resulting in drought durations over 18 months at Chatsworth, Weston Park and Rugby. The drought is most severe at Weston Park and Rugby, with peak severity in July and August 1874 (<-2.3).

4.3.4 1887-89 Drought

Five rainfall records are available to characterise the 1887-89 drought, Rhayader, Chatsworth, Weston Park, Rugby and Wall Grange. Based on the SPI-6 reconstruction (Figure 4.13a), the drought is initiated at Chatsworth in April 1887, at Rhayader, Wall Grange and Rugby in June, and at Weston Park in July. The drought is most severe at Chatsworth and Wall Grange, both sites have three continuous months of SPI values <-2 between June and August 1887. Conditions are less severe at all other sites suggesting this event is more intense in the northwest of the STR. Based on SPI-6 drought duration varies from 12 months at Weston Park to 15 months at Chatsworth. The drought is terminated at all sites by August 1888.

Based on SPI-12 results (Figure 4.13b), this drought shows intra-regional variation in duration and intensity. Duration ranges from 9 months at Rugby to 27 months at Wall Grange. At Chatsworth and Wall Grange drought onset occurs earlier (July 1887) than other sites (November 1887) and terminates later, April 1889 at Chatsworth and September 1889 at Wall Grange. Whilst peak drought intensity occurs at all sites in January 1888 with SPI values <-2, Chatsworth and Wall Grange experience extreme drought conditions for longest duration 7- and 8-months respectively. This is longer than other sites, ranging from 1-month at Rugby to 4-months at Rhayader. The period between February 1887 and January 1888 represents the lowest 12-month rainfall total (534mm) at Wall Grange between 1882 and 2012.

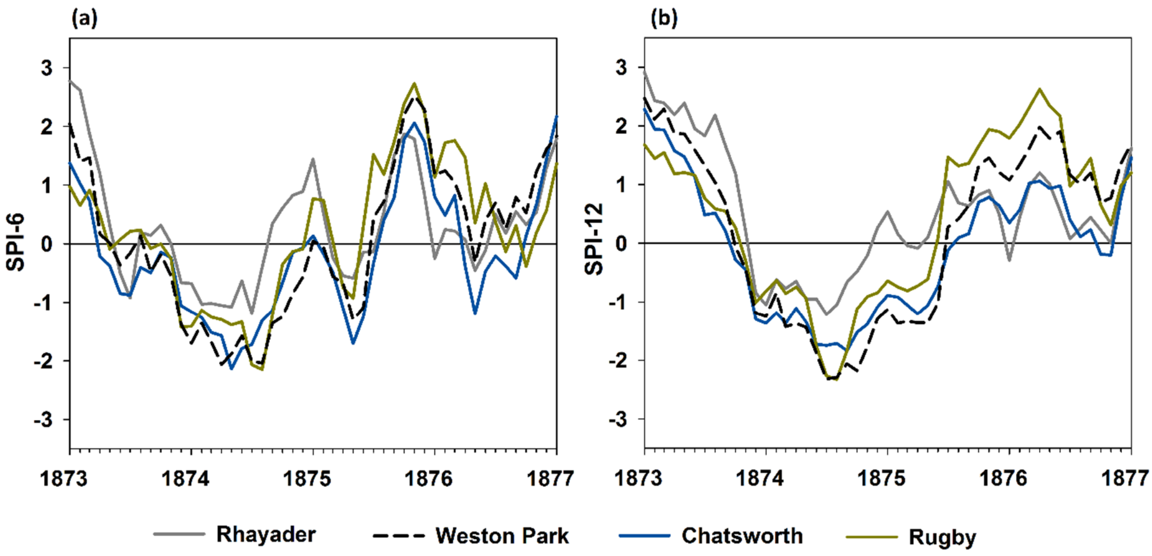

Figure 4.12: (a) SPI-6, (b) SPI-12 for 1873-75 drought

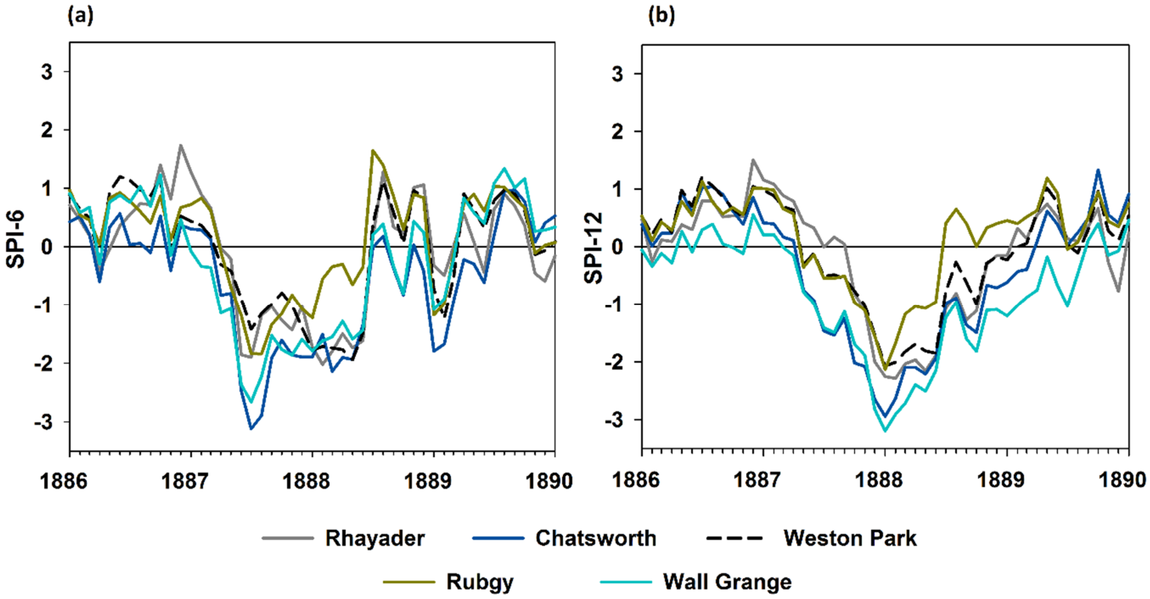

Figure 4.13: (a) SPI-6, (b) SPI-12 for 1887-89 drought

4.3.5 'The Long Drought' 1890-1910

'The Long Drought' coined by Marsh et al. (2007) is a series of long duration droughts punctuated by wetter episodes (Figure 4.14). The notable drought events (1890-1910) in the STR are 1890-91, 1892-97 and 1904-06. The 1890-91 and 1892-97 events are characterised using rainfall data from six sites (Rhayader, Chatsworth, Weston Park, Rugby, Wall Grange and Nanpantan; Figure 3.5a) and the 1904-07 event is characterised using all eight sites available for analysis in this chapter. Figure 4.14 identifies a further drought phase between 1899 and 1900, however, this has been excluded from this reconstruction because it does manifest across all sites in the STR.

1890-91 Drought

Using the SPI-6 (Figure 4.15a), this drought has two phases with distinct drought peaks (April 1890 and February 1891). At Rhayader, Chatsworth and Weston Park drought conditions are terminated for a 3-month period between November 1890 and January 1891; this results in two drought phases of 6- and 7-months. At Wall Grange and Nanpantan drought conditions are continuous resulting in a total duration of 17-months. Drought conditions at Rugby are only initiated during the second drought phase (January-September 1891) for a total duration of 7-months.

Based on the SPI-12 (Figure 4.15b) drought onset occurs between September and October at all sites except Nanpantan where the drought initiates earlier in April 1890. Nanpantan has the longest drought duration at 18-months and the lowest peak severity at -2.11 in October 1890. The drought is terminated at all sites by December 1891 excluding Chatsworth where termination occurs in June 1891.

1892-97 Drought

The 1892-97 event represents the longest duration drought in this reconstruction at Weston Park (47-months), Wall Grange (43-months) and Nanpantan (52-months) using the SPI-12 (Figure 4.16b). At Rhayader, Rugby and Chatsworth two distinct drought phases are punctuated by wetter conditions. Although the drought is not continuous at these three sites drought durations are still notable. At Rhayader the first drought phase is 15-months long with a second phase at 19-months. At Rugby the first phase is 23-months and the second 9-months. Chatsworth has the shortest duration first phase at 6-months with a second phase that is consistent with Rhayader at 20-months long. Drought onset occurs first at Rhayader, Rugby and Nanpantan in December 1892; at the remaining sites drought onset occurs between July and December 1893. Drought termination is initiated between February and April 1897 at all sites, excluding Weston Park, where termination occurs in August 1897. Based on the SPI-12 this drought is a long-duration, moderately severe event.

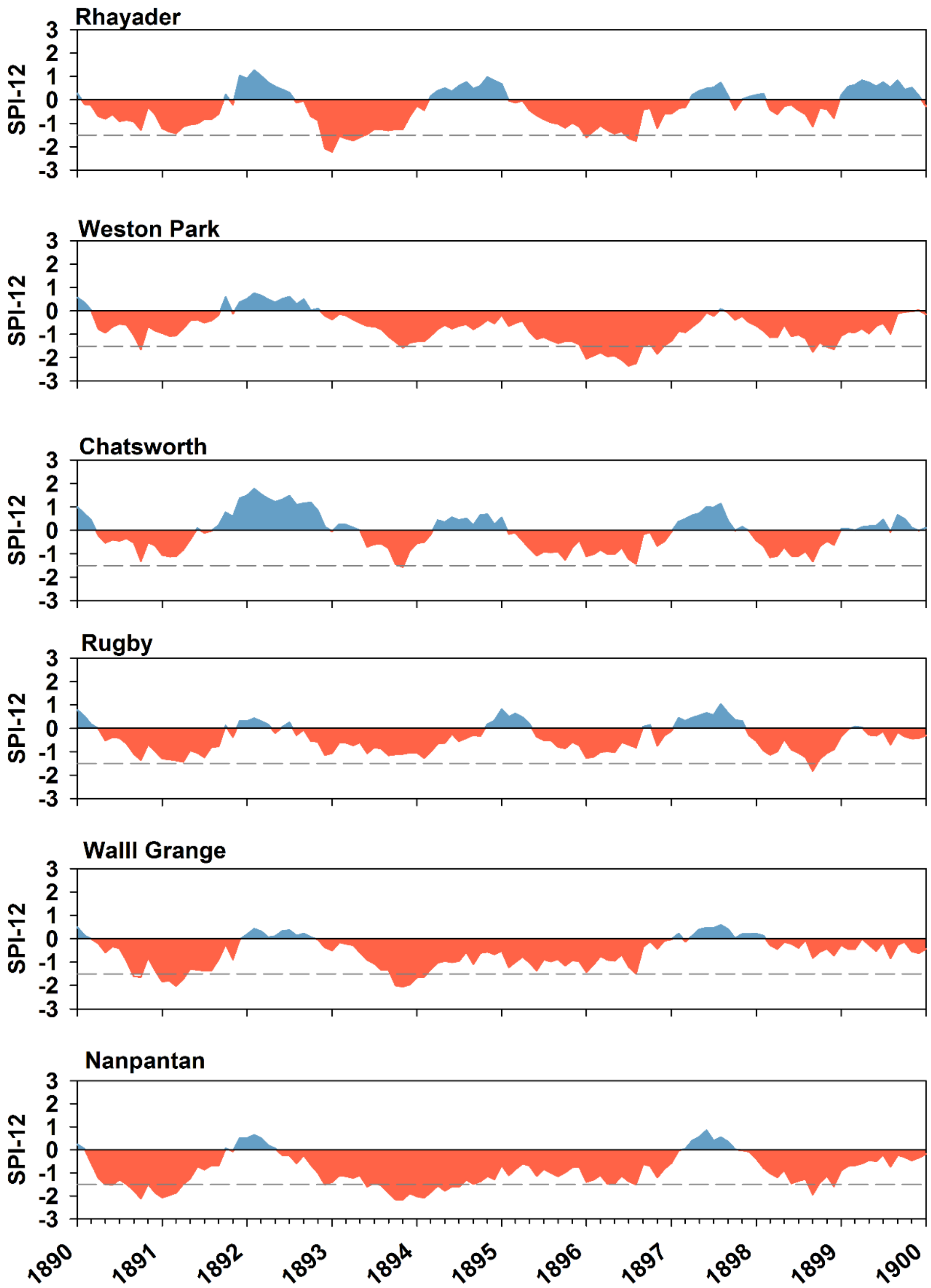

Figure 4.14: SPI-12 reconstruction of 1890-1900 component of 'The Long Drought' (1882-2012 analysis period)

Examination of the SPI-6 results (Figure 4.16a) reveals that between 1892 and 1897 there are a series drought phases with varying durations and severities. The longest drought duration in this period is 45-months at Nanpantan from January 1893 to September 1896. There appears to be a high level of intra-regional variability based on the SPI-6.

1904-08 Drought

The final notable event in the STR within 'The Long Drought' is the 1904-08 event. This drought is characterised at all eight rainfall datasets used in this chapter including Oakly Park and Nottingham. Based on the SPI-6 reconstruction (Figure 4.17a), there are two drought phases, 1904-05 and 1906-07. The onset of the 1904-05 phase occurs across the STR between August 1904 and December 1904, all sites reach a peak intensity (< -2) in February 1905. From March 1905 SPI values increase until termination occurs in August 1905 at all sites, excluding Nanpantan where the drought terminates in May 1906. The 1906-07 drought is shorter in duration, less severe and is identified at fewer sites than the 1904-05 phase. This second phase is most severe at Nottingham (<-2.17), Nanpantan (<-2.10) and Oakly Park (<-1.92).

Based on the SPI-12 (Figure 4.17b), the 1904-08 drought has a coherent onset occurring between October and November 1904 at all sites, excluding Nanpantan and Wall Grange, where it occurs in January 1905. Like the SPI-6 results, drought severity peaks at all sites in February 1905 with SPI values <-2. Drought termination is less coherent than onset. Between March 1905 and February 1906 SPI values increase at all sites, exceeding 0 at Chatsworth, Oakly Park and Rhayader for 1-month before becoming continuously negative throughout 1906. All sites reach a second drought peak in September 1906, SPI values fluctuate throughout 1907 and the drought is terminated at all sites by March 1908. Drought duration ranges from 32-months at Wall Grange and Nottingham to 40-months at Rhayader and Oakly Park.

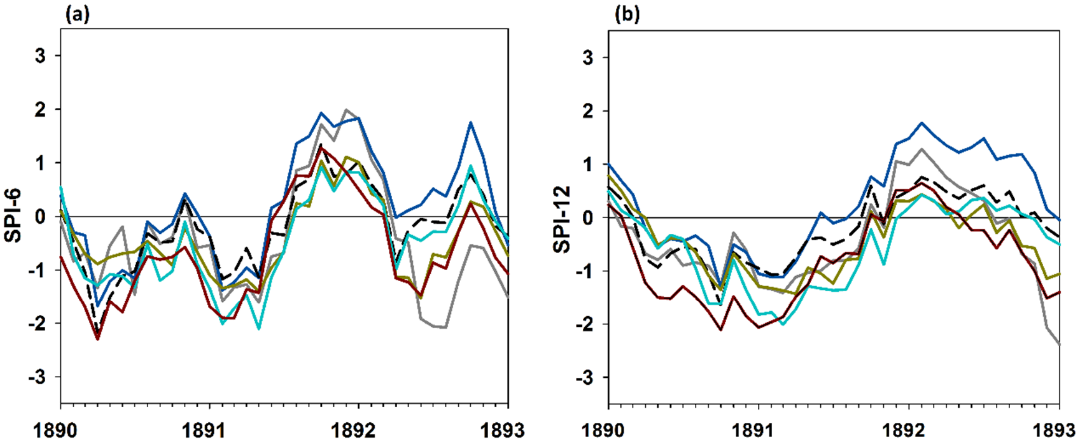

Figure 4.17: (a) SPI-6, (b) SPI-12 for 1890-91 drought

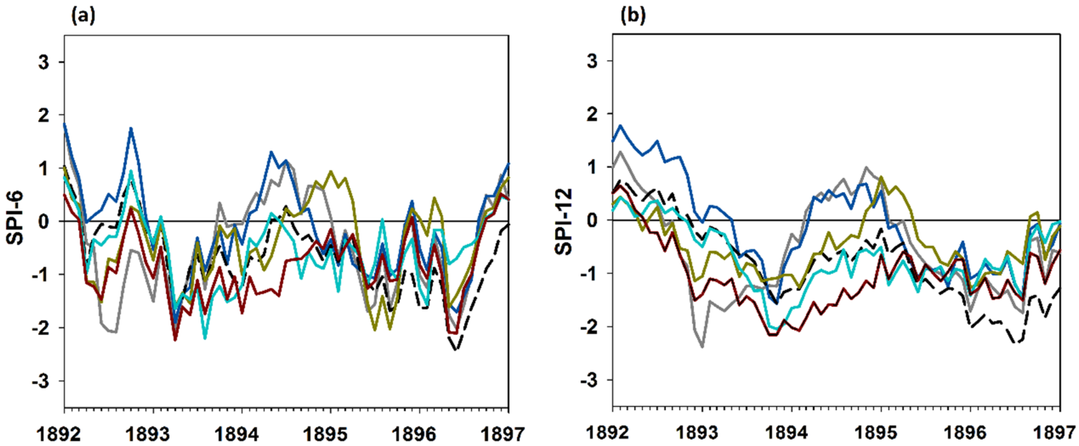

Figure 4.16: (a) SPI-6, (b) SPI-12 for 1892-97 drought

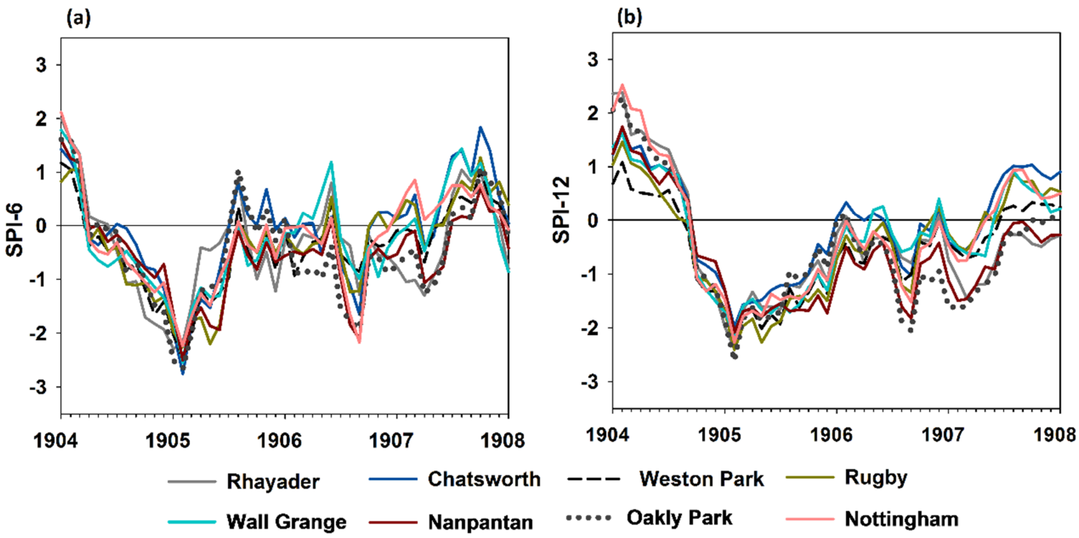

Figure 4.15: (a) SPI-6, (b) SPI-12 for 1904-08 drought

4.3.6 1920-23 Drought

The onset of the 1920-23 drought, based on the SPI-6, varies across the STR from November 1920 at Chatsworth to February 1921 at Weston Park and Oakly Park (Figure 4.18a). This event reaches peak intensity in June and July 1921 with SPI values <-2 at all sites, reaching <-3 at Oakly Park, Wall Grange and Rugby. The drought is terminated by April 1922 with drought durations ranging from 11- to 16-months. The exception to this is Chatsworth, where the drought conditions are not terminated until April 1923 giving a drought duration of 30-months. Drought severity at Chatsworth also differs from other sites, extreme drought (SPI <-2) is identified for 10-months between December 1920 and September 1921. July 1921 represents the lowest SPI-6 value for Chatsworth across all periods of reconstruction (1858-2012, 1900-2012 etc.) used in this chapter. The total rainfall at Chatsworth between February and July 1921 is 118 mm. July 1921 is also the lowest SPI value for Chatsworth using the SPI-12 reconstruction (Figure 4.18b).

The key difference between the SPI-6 and SPI-12 characterisation of this drought is duration, particularly at Rhayader, Oakly Park and Rugby where time from peak intensity to termination is significantly increased from 9 months to 27 months. Based on the SPI-12 drought duration across the STR can be categorised into two groups; (1) Weston Park, Wall Grange, Nanpantan and Nottingham with drought durations between 12- and 15-months and (2) Chatsworth, Rhayader, Oakly Park, Weston Park and Rugby with durations from 21- and 34-months.

4.3.7 1929 Drought

The 1928-29 drought (Figure 4.19) exhibits strong coherence across the STR based on SPI-6. Event onset occurs between February and April 1929 and termination occurs at all sites in November 1929. Drought duration varies between 7- and 9-months. Peak drought severity (SPI <-2) is reached at all sites in June 1929, between May and July all sites are in extreme drought (<-2). The SPI-12 reconstruction identifies a less severe drought with higher intra-regional variability. Event duration varies between 4- and 13-months, drought onset is more variable ranging from February to August 1929, whilst termination occurs at all sites between December 1929 and February 1930. Extreme drought (SPI <-2) conditions are only reached at Chatsworth and Nottingham.

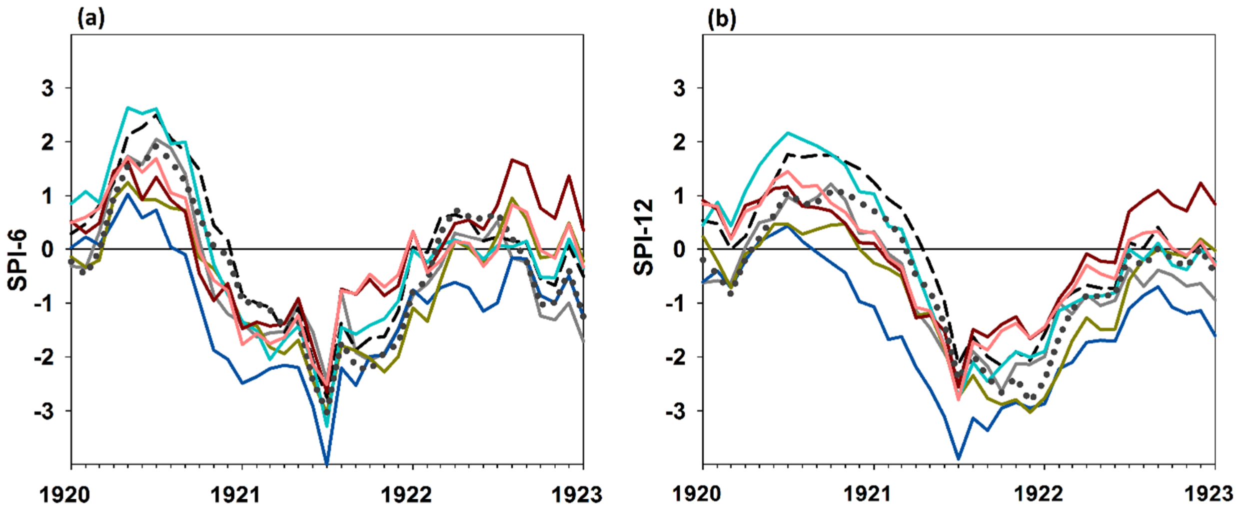

Figure 4.18: (a) SPI-6, (b) SPI-12 for 1921-22 drought

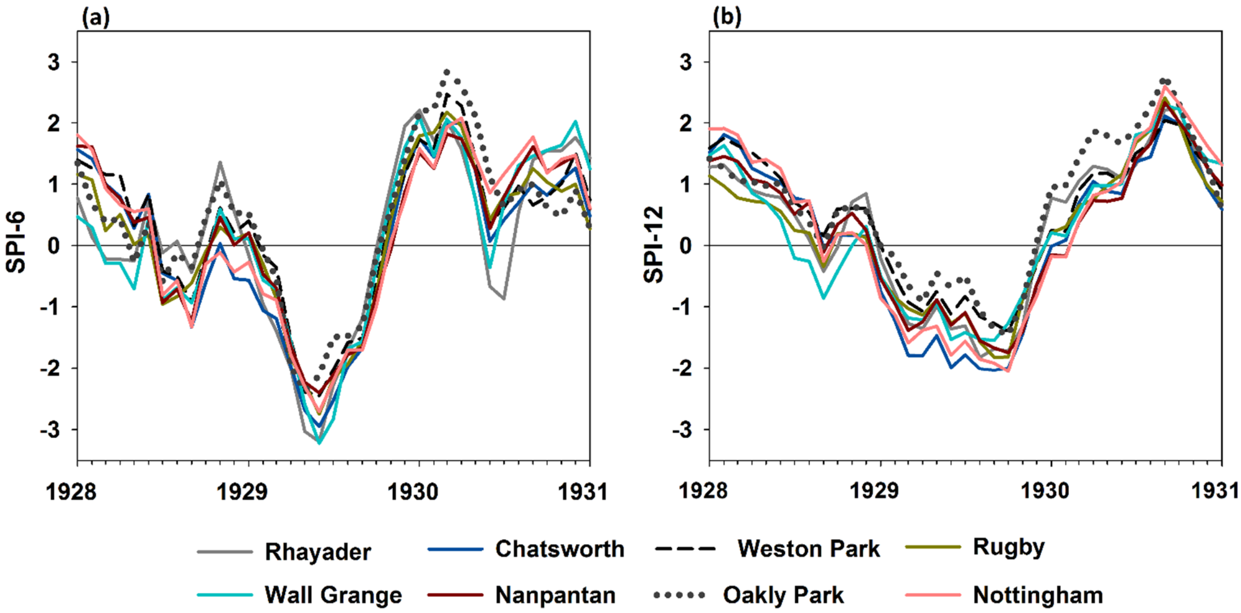

Figure 4.19: (a) SPI-6, (b) SPI-12 for 1929 drought

4.3.8 1933-35 Drought

The onset of the 1933-35 drought (Figure 4.20) occurs initially at Rugby in April 1933 with onset at all other sites, excluding Nanpantan, between August and September 1933. Drought onset at Nanpantan occurs last across the STR in December 1933. Based on the SPI-6, there is no distinct peak drought intensity for a single month, but a sustained period of SPI values <-2 at Rhayader, Wall Grange, Chatsworth and Rugby between December 1933 and July 1934. The duration of extreme drought (SPI <-2) at Wall Grange is 8-months, which is the longest continuous period of SPI values <-2 for Wall Grange in this SPI-6 reconstruction. Oakly Park, Weston Park, Nottingham and Nanpantan do not experience the same level of drought intensity over a sustained period. Drought termination starts first at Rhayader in August 1934 at all other sites drought termination occurs in 1935 between April and November. Based on the SPI-6 reconstruction, this drought event appears to have a high level of intra-regional variability, particularly the timing of termination and drought severity across the STR. Termination occurs in the west of the STR 15-months before Chatsworth in the north of the region.

The SPI-12 reconstruction also indicates intra-regional variation across the STR. Drought onset occurs between August and September 1933 across the region, excluding Weston Park and Nanpantan where onset starts in February 1934. At Rhayader, Wall Grange, Chatsworth and Rugby there is a sustained period extreme drought (SPI <-2) between November 1933 and November 1934 which is not identified at Oakly Park, Weston Park, Nanpantan and Nottingham indicating that the drought is less severe in the centre of the STR. Extreme drought conditions at Oakly Park, Weston Park, Nanpantan and Nottingham occur for 2-months (October and November 1934). At Rugby a peak intensity of -3.40 occurs in June 1934 this is the minimum SPI value at Rugby across the entire reconstruction, in the 12-months to June 1934 a total of 321 mm is recorded compared to an LTA (1961-90) of 644 mm. Drought termination occurs first at Rhayader in February 1935, followed by Rugby in June 1936. At all remaining sites drought termination occurs between October and November 1935.

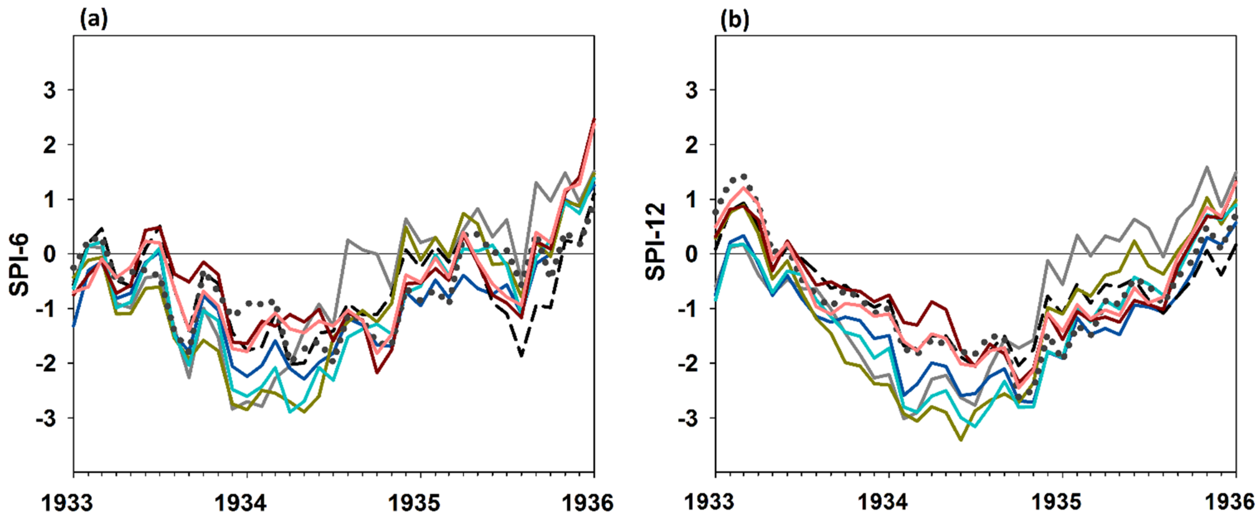

Figure 4.21: (a) SPI-6, (b) SPI-12 for 1933-35 drought

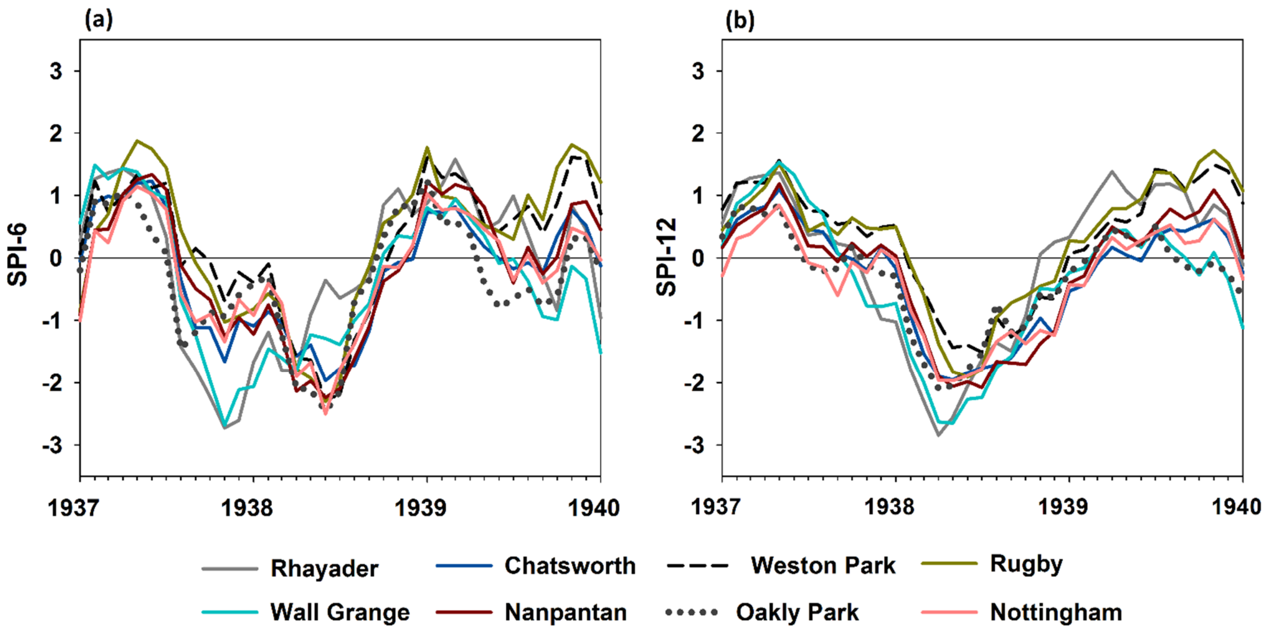

Figure 4.20: (a) SPI-6, (b) SPI-12 for 1937-38 drought

4.3.9 1937-38 Drought

The onset of the 1937-38 drought, based on the SPI-6, (Figure 4.21a) drought occurs in August and September 1937 in the west and north of the region at Rhayader, Oakly Park, Wall Grange, Chatsworth and Nottingham. Onset at Rugby and Nanpantan occurs later in November 1937, and the final site to reach drought conditions is Weston Park in April 1938. Two drought peaks are evident November 1937 at Wall Grange and Rhayader and June 1938 at Oakly Park, Weston Park, Chatsworth, Rugby, Nanpantan and Nottingham. Drought duration ranges between 13- and 15-months at all sites excluding Oakly Park at 6-months. The drought is terminated at all sites by December 1938. The SPI-12 reconstruction of this drought identifies onset occurrence across the STR between January 1938 at Rhayader and April 1938 at Weston Park and Rugby. Drought duration ranges from 9-months at Weston Park to 13-months at Oakly Park and Rugby. Extreme drought conditions are reached at Rhayader, Oakly Park, Wall Grange and Nanpantan. The drought terminated at all sites in the STR by April 1939.

4.3.10 1942-45 Drought

Both the SPI-6 and SPI-12 reconstructions identify a series of short duration drought phases throughout the 1940s, Marsh et al. (2007) also identify this across England and Wales, however they do not explore this further. This drought may have been under reported in the past owing to its occurrence during the second world war; during this time weather reports were subject to censorship as a source potentially significant military information. The most severe period is 1942-45 (Figure 4.22), SPI-6 results reveal a series of short duration, moderately severe (SPI <1.5-2) droughts in 1942. This is followed by a longer, more severe phase from mid-1944 to October 1947. SPI values reach <-2 at Rhayader, Oakly Park, Weston Park and Rugby.

SPI-12 reconstructions reveal inter-regional variation in drought onset, peak severity and termination. All sites enter drought during 1942, but onset varies from February 1942 at Rhayader in the west of the STR to November 1942 at Nanpantan and Nottingam in the east of STR. Drought conditions are sustained throughout 1943, although positive SPI values are reached at Rhayader, Oakly Park and Rugby for 1-month periods. Drought severity peaks during 1944, reaching <-2 at Rhayader, Weston Park, Rugby, Nanpantan and Nottingham. From September 1944 SPI values continue to increase with termination occurring first in the north of the STR at Wall Grange, Chatsworth and Nottingham in November 1944.

Termination occurs at all remaining sites by August 1945. Like the 1982-97 drought this event appears to be a long duration, moderately severe drought.

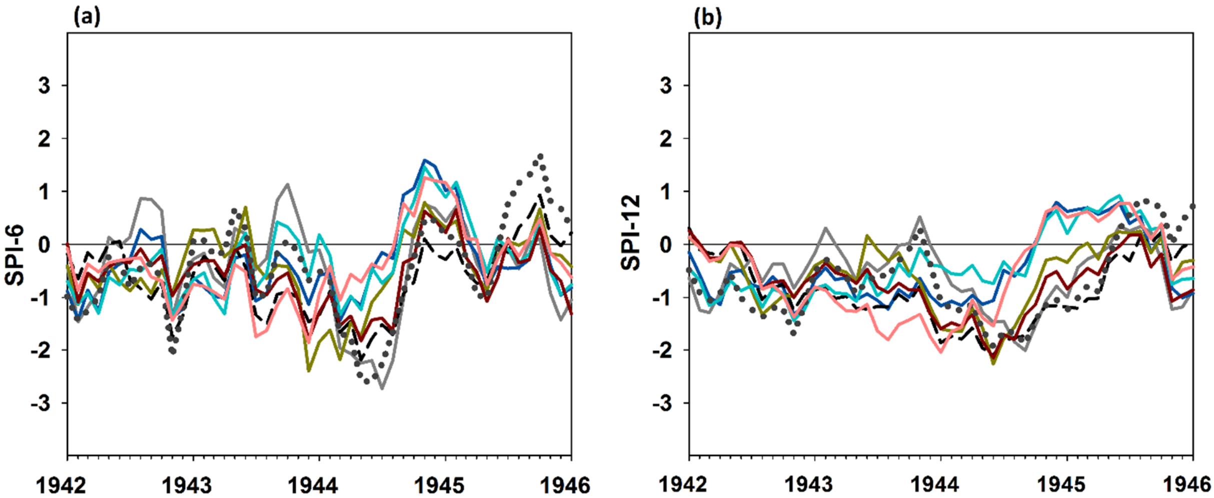

Figure 4.23: (a) SPI-6, (b) SPI-12 for 1942-45 drought

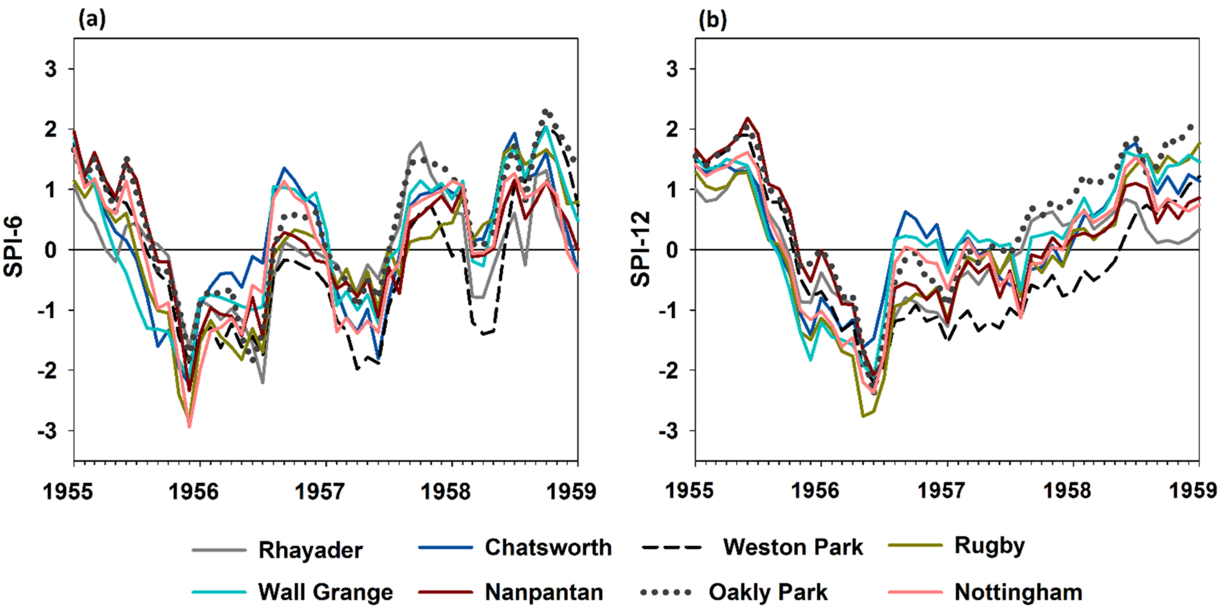

Figure 4.22: (a) SPI-6, (b) SPI-12 for 1955-57 drought

4.3.11 1955-57 Drought

Based on the SPI-6 (Figure 4.23a), there are two drought phases within 1955-57; (1) 1955-56 and (2) 1957. Onset of the first phase varies from August 1955 at Wall Grange to December 1955 at Rhayader and Oakly Park. Peak intensity occurs at all sites in December 1955, with SPI values in the east of the STR (Wall Grange, Chatsworth, Rugby, Nanpantan and Nottingham) below -2. From January 1956 SPI values steadily increase until the event is terminated at all sites (excluding Weston Park) by October 1956. Weston Park remains in drought throughout 1956 and into 1957 with a 22-month drought duration; at all other sites drought durations range from 9- to 11-months. The second drought phase is identified at all sites excluding Rhayader and Oakly Park in the far west of the region. This second phase is shorter in duration and less severe than the first phase, drought durations range from 2-months to 5-months.

The SPI-12 reconstruction of the 1955-57 drought (Figure 4.23b) results in an amalgamation of the two phases outlined above. The drought commences first at Wall Grange, Chatsworth, Rugby and Nottingham between November and December 1955, at the remaining sites onset occurs between March and May 1956. Peak drought intensity is reached in June 1956 with SPI value <-2 at all sites excluding Chatsworth. Drought duration is variable across the STR, ranging from 9-months at Chatsworth and Wall Grange to more than 20-months at Weston Park, Rugby and Nottingham.

4.3.12 1962-65 Drought

The 1962-65 drought exhibits similar characteristics to the 1955-57 drought, a series of short duration drought events in consecutive years (Figure 4.24a). SPI-6 results identify two notable drought phases, onset of the first phase occurs first at Rugby, Nanpantan and Nottingham in June 1962 and subsequently across the rest of the STR in January and February 1963, reaching a peak severity in March 1963. Drought termination is varied across the STR from June to November 1963. Event duration ranges from 6-months at Rhayader and Oakly Park to 17-months at Rugby, Nanpantan and Nottingham. Onset of the second phase occurs first at Rhayader, Oakly Park and Weston Park in the west of the STR in December 1963, followed by all remaining sites in February 1964. Rhayader, Oakly Park and Weston Park remain in drought throughout 1964. At all other sites the drought terminated for various durations during the summer (June, July and August); these sites re-enter drought in October 1964. Peak severity occurs in December 1964, SPI values fall below

-2 at Oakly Park, Weston Park, Rugby, Nanpantan and Nottingham. Termination occurs across the STR between May and July 1965, excluding Oakly Park where it occurs in January 1966.

The drought phases outlined above are amalgamated into a single drought event over a 12-month accumulation period (Figure 4.24b). Drought onset varies considerably across the STR from November 1961 to January 1963. Commencing first at Weston Park and Rugby in November and December 1961 respectively, this is followed by Nanpantan (February 1962), Nottingham (July 1962) and a lastly Rhayader, Oakly Park, Wall Grange and Chatsworth (January 1963). Peak drought intensity occurs at all sites in November 1964 with SPI values ranging from -1.5 (Wall Grange and Chatsworth) to -2.5 (Nanpantan). Drought termination occurs between September and October 1965 across the STR excluding Oakly Park, where it occurs in February 1966.

4.3.13 1975-77 Drought

Using the SPI-6, drought onset occurs between July and October 1975 across the STR excluding Oakly Park. Both the SPI-6 and SPI-12 reconstructions identify a series of short duration, moderate droughts across the STR in 1972-74 (Figure 4.25) that precede the 1975-77 event. However, at Oakly Park a drought initiated in 1974 is not terminated (unlike all other sites) so drought onset of the 1975-77 event is August 1974. Across all sites SPI values are continuously negative throughout 1976 with peak drought severity occurring in August 1976. At Rhayader peak drought severity reaches -3.5, this is the lowest SPI-6 value for this site from 1900-2012. The 6-month period to August 1976 also accounts for the lowest 6-month rainfall total at Rhayader from 1858 at 967mm compared to an LTA (1961-90) of 1603 mm for accumulated rainfall totals between March and August. Drought termination is rapid at Oakly Park, Weston Park, Wall Grange, Chatsworth and Rugby, occurring within 2-months of peak severity (October 1976). Termination is slower at Nanpantan and Nottingham in January 1977 and at Rhayader in February 1977.

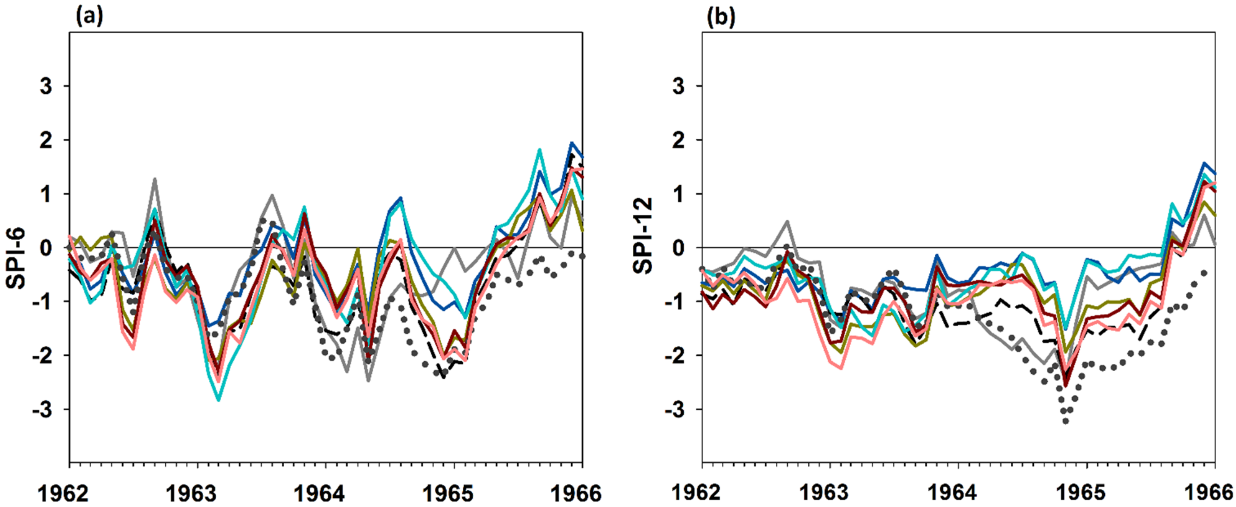

Figure 4.25: (a) SPI-6, (b) SPI-12 for 1962-65 drought

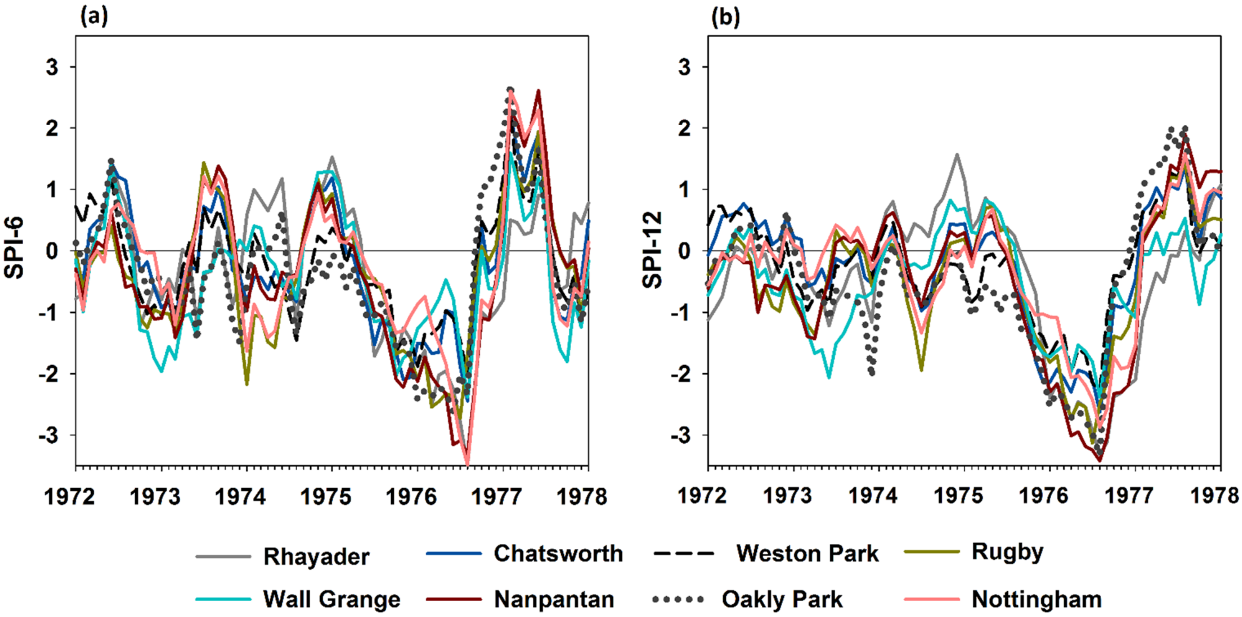

Figure 4.24: (a) SPI-6, (b) SPI-12 for 1975-77 drought

Based on the SPI-12 (Figure 4.25b) drought onset occurs between September and December 1975 across the STR excluding Oakly Park where it occurs earlier in February 1975. Like the SPI-6 reconstruction peak drought severity is in August 1976 with all sites in extreme drought; at Rhayader, Oakly Park and Nanapantan SPI values reach <-3. At Rhayader, Oakly Park, Nanpantan and Nottingham rainfall totals in the 12-months to August 1976 are the lowest recorded at each site across the reconstruction period. At Nanpantan and Rhayader SPI values are <-2 throughout in 1976, at 12- and 13-months respectively these periods are the longest 'extreme' drought sequences in the reconstructions for these sites. Drought termination occurs between January and February 1977 across the STR, excluding Wall Grange in April 1977 and Rhayader in August 1977. Total drought durations range from 14-months at Weston Park to 23-months at Oakly Park.

4.3.14 1990-92 Drought

The SPI-6 reconstruction identifies two drought phases across the STR between 1990 and 1992 (Figure 4.26a). The first phase occurs between July 1990 and February 1991 with drought durations ranging from 6- to 8-months across the STR excluding Rhayader; at this site drought conditions are only experienced in August and September 1990. Peak intensity occurs during August and September 1990, with extreme drought conditions (SPI <-2) experienced at Oakly Park, Weston Park, Chatsworth, Rugby and Nanpantan. The onset of the second drought phase is less coherent than the first phase, onset occurs first at Wall Grange (May 1991) and last at Rugby (January 1992). The longest drought durations are in the north of the STR at Wall Grange (11-months), Chatsworth (12-months) and Nottingham (14-months). Drought conditions are terminated across the STR by August 1992.

Based on the SPI-12 (Figure 4.26b), the 1990-92 drought exhibits similar characteristics to the 1955-57 and1962-65 droughts; a long duration moderately severe event. Drought onset is variable across the STR, ranging from September 1990 at Rugby to September 1991 at Wall Grange. Event duration ranges from 12-months at Wall Grange to 24-months at Oakly Park and Chatsworth. The drought is terminated at all sites by January 1993. No drought conditions are experienced at Rhayader between 1990 and 1992 when using the SP1-12; whilst this appears anomalous, these results are consistent with SPI-12 results at Clywedog (for the period 1962-2012), which is approximately 21 km north of the rain gauge at Rhayader.

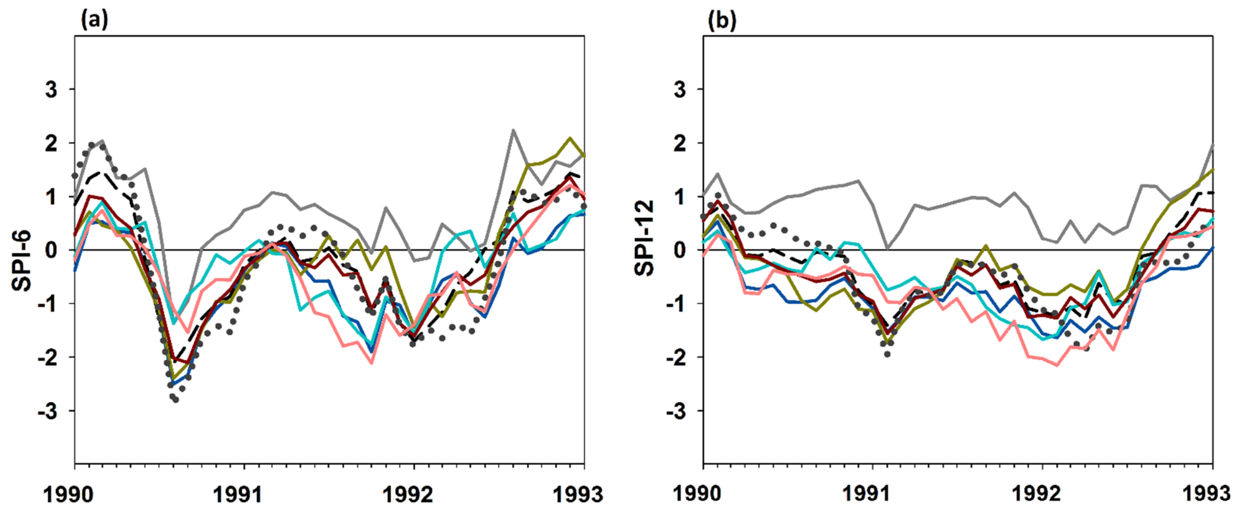

Figure 4.27: (a) SPI-6, (b) SPI-12 for 1990-92 drought

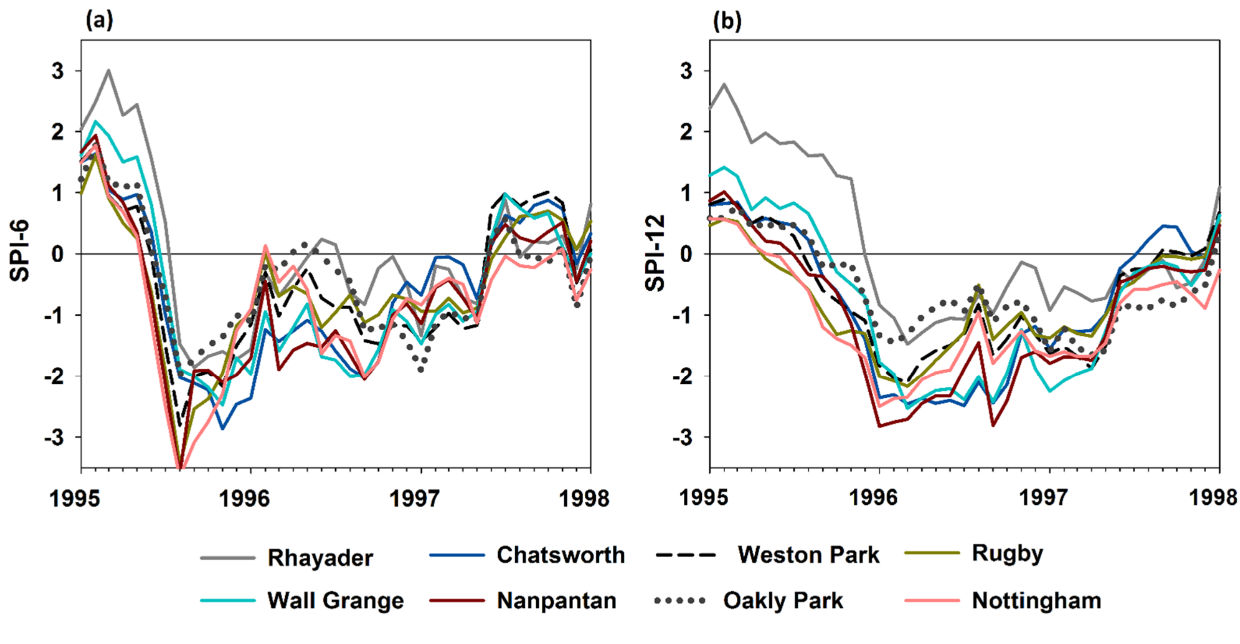

Figure 4.26: (a) SPI-6, (b) SPI-12 for 1995-97 drought

4.3.15 1995-97 Drought

The 1995-97 drought (Figure 4.27) exhibits a dramatic drought onset based on the SPI-6 reconstruction. In January and February 1995, SPI values across the STR are >1.5 indicating very wet conditions, but within 7-months (August 1995) all sites are classified in severe or extreme drought. Intra-regional variability in drought severity is identified, with the least severe conditions in the west of the STR. In the east of the STR at Rugby, Nanpantan and Nottingham SPI values are <-3 in August 1995, the 6-months to August 1995 account for the lowest rainfall totals recorded at these sites during the total period of reconstruction. From September 1995 to January 1996, SPI values are increasingly positive before decreasing again throughout 1996. The drought terminates across the STR in July 1997 excluding Nottingham where it occurs in November 1997. Drought duration ranges from 22-months (Rhayader, Oakly Park, Wall Grange, and Chatsworth) to 29-months at Nottingham.

Based on the SPI-12, the onset of the 1995-97 drought occurs earliest (September to November 1995) in the east of the STR at Rugby, Nanpantan and Nottingham and occurs last in the west of the STR at Oakly Park (January 1996) and Rhayader (February 1996). Drought severity peaks in March 1996 with SPI values reaching <-2 at all sites except Rhayader and Oakly Park. At Chatsworth, Wall Grange and Nanpantan SPI values remain <-2 throughout 1996 for 10-, 9- and 8-months respectively. Drought termination is variable across the STR, occurring first at Chatsworth in August 1997, it is terminated at the majority of sites in January 1998 and lastly in April 1998 at Nottingham.

4.3.16 2010-12 Drought

The 2010-12 drought is the most recent drought event experienced in the STR. The SPI-6 reconstruction (Figure 4.28a) identifies two drought phases, the first phase between May and October 2010 is not identified at Rugby, Nanpantan and Nottingham in the east of the STR. The second drought phase is initiated in either March or April 2011 at all sites excluding Rhayader and Weston Park. At Weston Park there is a single drought phase from January 2010 to March 2012 (27-months). At Rhayader three short drought phases are identified; (1) 6-months (May – October 2010), (2) 4-months (May to August 2011) and (3) 3-months (March – May 2012). Drought conditions persist across the STR throughout 2011 and into early 2012, with event termination occurring in either April or May at all sites. The termination of this drought is rapid; by July 2012 SPI values are in excess of >1.5 across all sites and exceed >2.5 in the east of the STR. Drought durations for the 2011-12 drought phase range from 15-months at Oakly Park to 12-months at Wall Grange and Nanpantan.

The drought phases described above are amalgamated into a single drought event when using the SPI-12. Drought onset exhibits considerable intra-regional variability, occurring first at Weston Park and Wall Grange (July 2010), Rhayader and Oakly Park (December 2010), Chatsworth and Nanpantan (March and April 2011) and lastly Rugby and Nottingham (August 2011). Across the STR, SPI values steadily decrease to a peak drought intensity in November 2011 with SPI values <-2 at all sites excluding Rhayader and Wall Grange. At Oakly Park, Weston Park and Nanpantan SPI values remain <-2 for 7-months between August 2011 and March 2012. Drought termination occurs at all sites between June and August 2012. Drought durations are longest at Weston Park (25-months) and Wall Grange (23-months and shortest at Rugby (10-months) and Nottingham (9-months). The variation in the drought duration across the STR reflects the presence of the 2010 drought phase in the west of the region identified using the SPI-6.

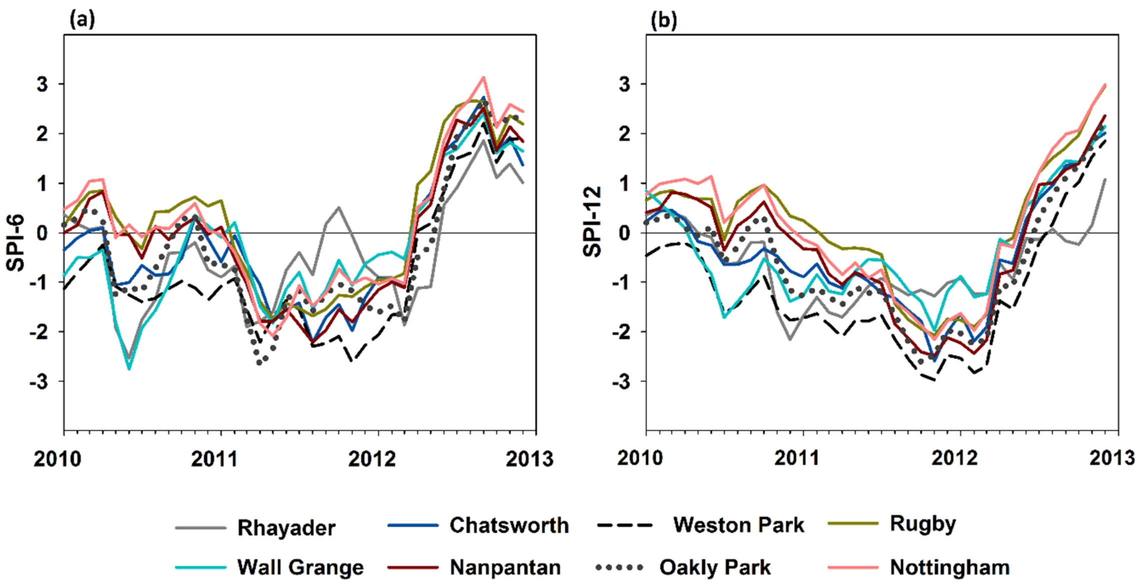

Figure 4.28: (a) SPI-6, (b) SPI-12 for 2010-12 drought

4.3.17 Major Droughts and Drought Typologies

This high resolution reconstruction of meteorological drought across the STR identifies 19 drought events with durations greater than 10-months (based on the SPI-12). Droughts are not a rare phenomenon in the STR and are experienced in every decade between the 1860s and 2010s with the exception of the 1910s and 1980s. However, only a few of these events appear to be notable in terms of duration or severity. Two distinct drought typologies that require further examination are identified; (1) long-duration, moderate severity droughts, and (2) moderate-duration, extreme severity droughts.

Of the 19 events identified, five droughts can be considered as the most severe in terms of 12-month rainfall totals (minimum SPI values) and substantial drought durations (between 15- and 29-months) *(1) 1862-66, (2) 1887-89, (3) 1921-23, (4) 1933-35 and (6) 1975-77*. Table 4.5 provides a summary of these severe droughts including 12-month rainfall totals and deficit volumes associated with the lowest SPI-value identified at each site. During the most severe drought at each site between 60% and 45% of the 12-month average long-term (1961-1990) rainfall total is recorded. The 'benchmark' 1975-77 drought is the most severe event at four of the eight sites across the STR; the most severe droughts at the remaining four sites are the 1862-66, 1887-89, 1920-23 and 1933-35 droughts. This highlights the need to examine a range of droughts experienced in the STR when examining drought risk. This need is particularly important for historic droughts not commonly analysed in operational water resources management e.g. long duration drought events.

Examples of long -duration, moderate severity droughts include 1892-97, 1904-08, 1942-45 and 1962-65 with drought durations of up to 51-months (based on the SPI-12). Characterising these droughts based on the SPI-6 reveals that they appear to be formed of a series of short duration drought phases that are amalgamated into a single long duration drought when examined over a 12-month rainfall accumulation period (SPI-12). Whilst these droughts are less severe than those discussed above (1862-66, 1887-89, 1921-23. 1933-35, 1975-76) it would be beneficial to further understand the impact of very long duration, moderate severity droughts on water resources. Section 4.3 presents an application of an SPI-12 drought reconstruction to identify major droughts (both very long duration, moderate severity and long duration, extreme severity events) in the STR with a focus on a single Water Resource Zone (WRZ) to model reservoir storage and deployable output using long-series rainfall data constructed for this thesis.

Table 4.5: Most severe meteorological drought for each site (1858-2012)

Drought	Site	Date	Min SPI-12 Value	12-month Rainfall Total (mm)	LTA 1961-1900 (mm)	Deficit (mm)	% LTA	Drought Duration (months)
1862-66	Weston Park	November 1864	-2.8	408	723	315	56	29
1887-89	Wall Grange	January 1888	-3.1	534	919	385	58	27
1920-23	Chatsworth	July 1921	-3.4	387	857	470	45	21
1933-35	Rugby	June 1934	-3.5	321	644	323	50	22
1975-77	Rhayader	August 1976	-3.3	967	1600	633	60	20
	Nottingham	August 1976	-2.8	370	706	336	52	15
	Nanpantan	August 1976	-3.4	416	741	325	56	16
	Oakly Park	August 1976	-3.3	358	611	253	59	23

4.4 "The Application of a Drought Reconstruction in Water Resource Management"

(Lennard A.T., Macdonald N. Clark S. & Hooke J.M., 2016. The application of drought reconstruction in water resource management, *Hydrology Research,* 7(3):646-659, doi: 10.2166/nh.2015.090)
The peer reviewed paper is reproduced below representing section 4.4 of the thesis, the only modifications being that the figure and table numbers run concurrent to the thesis.

4.4.1 Abstract

This study uses extended (1880s–2012) rainfall series to examine the implications of historical droughts on water supply yield calculations used in water resource management and drought planning across the English Midlands and Central Wales. UK guidance to water companies is to use climate data from the 1920s to present where possible in modelling to inform water resource management and drought plans; but this period excludes several major droughts of the late nineteenth century. This study uses the standardised precipitation index and hydrological modelling (HYSIM and AQUATOR) to investigate the implications of pre-1920s droughts on water resource management. Although drought characterisation identifies two significant droughts in the pre-1920 period, the impact of these events on reservoir storage is less severe than droughts identified in the post-1920 period, indicating that the use of long climate series in water resource modelling is a valuable tool in assessing the robustness of current water resource modelling used in the water resource sector.

4.4.2 Introduction

Drought is a recurring feature of the UK climate. There have been a number of notable drought events throughout the twentieth and twenty-first centuries (1921–1922, 1933–1934, 1975–1976, 1995–1996, 2004–2006, 2010– 2012) that highlight the UK's vulnerability. To maintain public water supplies throughout periods of flooding and drought, water supply systems are designed to smooth natural climate variability (Watts et al. 2012). Water resource management includes the use of modelling approaches to simulate water supply systems in order to define the yield, or deployable output (DO), of the water resource system. Environment Agency guidelines state that the assessment of yield should use data from at least 1920 onwards so as to incorporate a number of extreme events. However, this period excludes a number of notable droughts during the late nineteenth century, including a particularly severe drought (1887–1889) and the 'Long Drought' (1880–1910) as identified by Marsh et al. (2007).

Under UK legislation, water companies in England and Wales are required to produce water resources management and drought plans to outline how they intend to manage water supplies. Water resources management plans (WRMPs) are produced every five years to define how a water company plans to manage and ensure the security of water supplies over the next 25 years (Environment Agency, 2012d). Whilst drought plans are produced every three years, these plans outline the short-term measures required to manage water supplies before, during and after a drought, whilst minimising impacts on the environment (Environment Agency, 2012d). A key component of water resource management and drought plans is the calculation of DO. This is defined by the Environment Agency (2012) as 'the output for specified conditions and demands of commissioned source, group of sources or water resources system as constrained by hydrological yield, licensed quantities, environment, pumping plant/or well/aquifer properties, transfer/or output mains, treatment, water quality and levels of service.'

The UK has a wealth of long climate data series that are currently under-used in water resource management. A number of drought reconstructions have been undertaken (Wells et al. 2004; Marsh et al. 2007; Todd et al. 2013 – an approach applied by Severn Trent Water 2014a, p. 35), but little of this information is used to inform water resource management. To date, few studies have applied long-series climate data for water resource management; the exceptions being Watts et al. (2012) and Spraggs et al. (2015). Watts et al. (2012) used long severe UK droughts of the nineteenth century to test water resource systems resilience; whilst Spraggs et al. (2015) used a drought reconstruction (1789–2010) to examine long-term yield or DO for the Anglian Region (UK). The study highlights that the temporal and spatial characteristics of drought variability should be taken into account in water resource management, with an assessment of the water supply system required at local and regional scales. The use of long climate series with an increased number of drought events is valuable in testing the robustness of water resource modelling. Each drought has a unique set of characteristics that may affect a water resource system in different ways. For example, the sequencing of wetter and drier periods during a drought is an important factor in the performance of a supply system (Watts et al. 2012). Marsh et al. (2007) emphasise that characterisation of droughts experienced prior to 1914 could be a useful addition to water resource management strategies.

This paper aims to characterise past drought events from the 1880s to 2012 for the English Midlands and central Wales. Drought characterisation is used to extend the water resources modelling period from 1920–2012 to 1884–2012 for a single water supply zone, within the Severn Trent Water region, permitting investigation of the impacts of pre-1920s droughts on reservoir yields and exploring how meteorological and hydrological drought characteristics impact the water supply system.

4.4.3 Data and Methods

Study Area

The Severn Trent Water supply region, spanning central England and mid-Wales, is approximately 21,000 km2, with a varied topography, which includes uplands over 800 m above sea level (m a.s.l) in the north and west; a central plateau region between 100 and 250 m a.s.l; with the south and the east of the region situated within the English Lowlands (~50 m a.s.l.). Considerable spatial variation in rainfall exists across the region, ranging from over 1,800 mm in the Welsh uplands to ~650 mm in the southeast of the region (Met Office, 2014). Several large towns and cities are within the supply area including Birmingham, Nottingham, Leicester and Stafford (Figure 4.29). Severn Trent Water supplies approximately 7.4 million people with potable water provision sourced from reservoirs, river abstractions and groundwater, each contributing approximately one third of total supply. The water supply region is divided into 15 water resource zones (Severn Trent Water, 2012a). These zones are defined by the regulating bodies as 'the largest possible zone in which customers share the same risk of a resource shortfall' (OFWAT, 2004). This study explores the implications of using long climate data in water resources assessments for just one of these zones: the North Staffordshire Water Resource Zone. Supplying water for a population of approximately 523,000 people, water provision in this resource zone is sourced from both groundwater and an impounding reservoir (Tittesworth Reservoir) on the headwaters of the River Churnet. The Severn Trent Water drought plan (Severn Trent Water, 2012b) identifies that within this water resource zone the 1933–1935 drought had the greatest impact on simulated reservoir storage over the baseline modelling period (1920–2010).

Rainfall

Five long-term daily precipitation series (Figure 4.29) are available for the study area (British Atmospheric Data Centre, 2014). The rainfall series extend back into the nineteenth century, but vary in length accordingly: Wall Grange (A; 1882–2012), Chatsworth Gardens (B; 1887–2012), Nanpantan Reservoir (C; 1887–2012), Rugby (D; 1872–2012) and Rhayader (E; 1858–2012) (Figure 4.29). Site E lies outside of the water supply region, however, it is located near the Elan Valley reservoir system that supplies water into the study region. These sites are selected based on length of record, the percentage of missing data (sites with more than 20% missing data were rejected) and the identification of nearby weather stations to provide missing data through infilling (Peterson et al., 1998), with each dataset quality control checked for any data gaps, duplicate entries and erroneous data. Data gaps were filled using linear regression techniques and additional data from the nearby weather stations to produce suitable data based on the relationship between the primary and the secondary station rainfall data (Macdonald et al., 2008). Each rainfall series used to fill gaps are within 10 km of the primary weather station. Re-constructed rainfall series were checked for homogeneity, trend and randomness. Inhomogeneous records may be a result of climatic variability or human influence, which include changes in instrumentation. Trend detection was undertaken using the Mann–Kendall trend test to assess for artificial trends in the data that could cause inhomogeneity. Distribution-Free CUSUM was used to test for step jump in annual mean and Rank Difference was used to test for randomness.

The use of long series rainfall data does not come without some uncertainty. For example, Spraggs et al. (2015) note the issue of rain gauge under-catch caused by snowfall during winter months particularly during cold winters in the early nineteenth century. Under-catch due to snow may pose a greater issue in Severn Trent Water study region, particularly amongst rain gauges in upland mid-Wales and the Peak District. Under-catch due to snow remains an uncertainty particularly for rainfall-runoff modelling where runoff signatures can be altered by precipitation stored as snowpack.

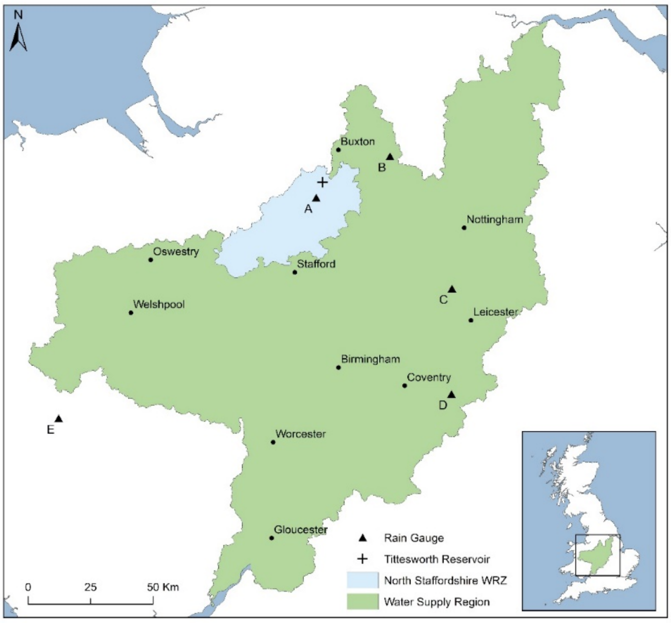

Figure 4.29: Study area, location of weather stations and location of NSWRZ

PET

Potential evapotranspiration (PET) is required for rainfall–runoff modelling; it is estimated within this study at a monthly time step, using mean monthly temperature data from the Hadley Centre Central England Temperature (CET) series (Parker et al., 1992). The CET includes daily and monthly minimum, maximum and mean temperatures based on a composite set of measurements that are representative of a triangular area roughly bounded by Bristol, Lancashire and London (Manley, 1974). Whilst concerns have been raised about the applicability of this series away from the central England region (Macdonald et al., 2010), much of the study area falls within the CET area. The Thornthwaite equation is applied to estimate PET (Thornthwaite, 1948) this method requires mean monthly temperature and station latitude, used to calculate the maximum amount of sunshine hours. Monthly PET estimates are calculated for the period 1882–2012 in order to extend the PET data for rainfall-runoff modelling. PET data used in the 1920–2010 modelling is a combination of Met Office Surface Exchange Scheme PET data (MOSES data) (1961–2010) and calculated PET (1918–1961). MOSES data calculates water and energy fluxes at the earth's surface using a four-layer soil model and the Penman–Monteith equation to calculate PET (Cox et al., 1999).

Thornthwaite PET data for the period 1882–2012 are compared against the baseline (1920–2010) PET data; this indicated slight variations between the two data sets; October–April exhibited similar values, May–September PET are typically 10% lower for the Thornthwaite PET dataset. To ensure consistency between the Thornthwaite PET data and baseline (1918–2010) PET data, a modification factor reducing monthly Thornthwaite PET by 10% is applied to the May–September months between 1882 and 1918.

Drought Characterisation

Drought indices are a commonly used approach to monitor and characterise drought conditions, with a number of different indices applied globally, subject to the type of drought and data availability for an area (a detailed review of drought indices is provided by Heim (2002) and Mishra & Singh (2010)). The standardised precipitation index (SPI), developed by McKee et al. (1993), uses rainfall data to quantify precipitation deficit or excess across different climates and at multiple timescales, typically of 1–24 months. These timescales reflect the impacts of drought on various water sources; for example, soil moisture deficit responds at a faster rate than streamflow and groundwater. The standardised nature of the SPI allows for the comparison of drought conditions at different locations and between seasons.

The SPI is computed using the following steps:

1) Fit a probability density function to selected accumulation period (e.g. 12 months rainfall totals/climatic water balance). A gamma probability distribution was found to be the most appropriate fit for the SPI in this case using a Kolmogorov–Smirnov (K–S) test to compare how well the empirical probability function corresponds to the theoretical cumulative probability function of each dataset (Lloyd-Hughes & Saunders 2002; Vicente-Serrano et al. 2010; Sienz et al. 2012). Several other univariate distributions have also been recommended (Vicente-Serrano et al. 2010; Stagge et al. 2015a).

2) Equiprobabilty transformation of the cumulative probability of the fitted distribution to standard normal distribution to define the SPI value, giving a mean of 0 and a standard deviation of 1.

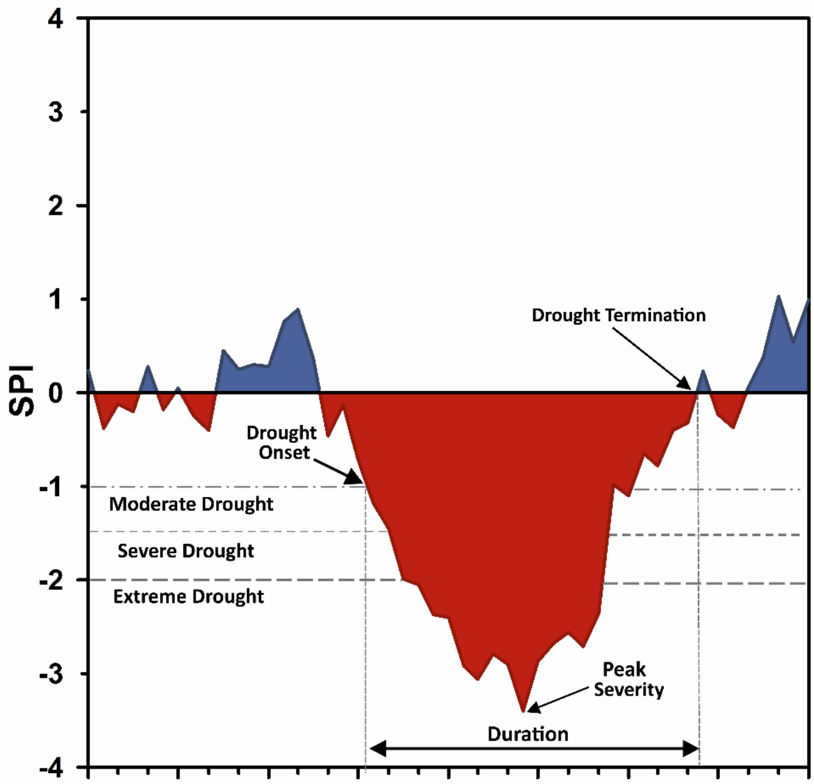

Figure 4.30: Drought classifications and characteristics

SPI values are dimensionless units, negative values indicate drier than normal conditions and positive values wetter than normal conditions. In this study drought onset is assumed to occur at an SPI value equal to or less than −1.00 and drought termination is assumed to occur when the SPI returns to 0 or more (Figure 4.25). The SPI can be used to characterise drought duration, severity and timing of onset and termination. The characterisation is based on the classifications identified in Figure 4.25. Drought duration is considered to be the number of months of between drought onset at SPI −1.00 or less and a return to SPI 0 or more, drought severity categorised using the SPI classification system (Figure 4.30) and peak severity the minimum SPI value recorded during the drought event.

The SPI was computed for multiple timescales – 3-, 6-, 9- and 12-months – these were compared to identify the most suitable accumulation period. The SPI-12 is well suited to characterising the longest, most significant drought periods. Longer SPI timescales result in a decrease in frequency and increase in duration of individual drought events, with timescales of <6 months masking the most significant drought events, reflecting short term variability in precipitation. This is in agreement with Vicente-Serrano & Lopez-Moreno (2005) who established that identifying the most important droughts requires a timescale greater than six months.

This study uses SPI-12, which has been commonly used as an appropriate timescale to reflect the impact of meteorological drought on surface water resources (Hayes et al. 1999; Szalai et al. 2000; Santos et al. 2011; Gocic & Trajkovic 2014). Five long SPI-12 series are generated using precipitation series (sites A–E) to characterise drought events (drought duration, severity and timing) for individual sites and to establish temporal and spatial patterns across the region.

Globally the SPI has been used in numerous studies tocharacterise droughts (e.g. Lloyd-Hughes & Saunders 2002; Livada & Assimakopoulos 2006; Dubrovsky et al. 2008). Within the UK, numerous drought metrics have been used to characterise droughts including the SPI. Previous studies have applied the Palmer Drought Severity Index to re-construct drought in south-east England (Todd et al. 2013) and the Drought Severity Index was used for south-west England (Phillips & McGregor 1998), northern England (Fowler & Kilsby 2002) and across the UK (Rahiz & New 2012a).

Examples of the application of the SPI in the UK include Bloomfield & Marchant (2013) and Folland et al. (2015). Bloomfield & Marchant (2013) use the SPI in the development of a standardised groundwater index methodology. Folland et al. (2015) characterise multi-annual droughts in the English Lowlands using a number of standardised drought indicators including the SPI. Lennard et al. (2014) applied the SPI to analyse drought characteristics in the English Midlands using a short rainfall series (1962–2012), which identified three multi-year droughts (1975–1976, 1995–1997 and 2010–2012) that exhibited spatial and temporal variation across the study region. Whilst this presented some novel results, the instrumental record length (1961–2012) provided insufficient information for informing management decisions. However, the SPI has not been widely used for operational water resource management in the UK.

Water Resource Modelling

Water resource modelling for the assessment of yield requires two processes: (1) rainfall–runoff modelling to simulate river flow and reservoir inflow; and, (2) water supply system modelling to determine yields required to meet water demand. This study utilises the modelling approaches used by Severn Trent Water for their Water Resource Management Plans and Drought Plans following Environment Agency guidelines (Environment Agency, 2012d). To assess water resource planning options Severn Trent Water use a modelling approach that combines the runoff-rainfall model HYSIM, and the commercial water resources model Aquator. Further information on the Severn Trent Water modelling methodologies are detailed in their WRMP 2014 (Severn Trent Water 2012a). Current yield assessments undertaken by Severn Trent Water use data for the period 1920–2010, the reference baseline modelling/data throughout this paper. Yield assessment to extend water resource modelling (inflows into Tittesworth from the Churnet headwaters) for the North Staffordshire water resource zone (NSWRZ) for the period (1884–2012) is referred to as extended modelling/data.

The key differences between the modelling used by Severn Trent Water and the modelling used in this study are:

1) Yield assessment for the NSWRZ is extended from the baseline 1920–2010 (90 years) to 1884–2012 (128 years);
2) Rainfall data from site A (Figure 4.24) from the 1880s is used to extend rainfall data applied by Severn Trent Water in baseline modelling (1920–2010);
3) PET is calculated to extend PET data used by Severn Trent Water.

Rainfall-runoff Modelling

HYSIM is a conceptual rainfall–runoff model used to model daily streamflow into Tittesworth Reservoir using rainfall data, PET and a number of catchment parameters. The model includes a linked set of storages including interception, upper soil, lower soil and groundwater (Water Resource Associate Ltd. 2006). Catchment parameters include catchment area, soil pore size distribution, rooting depth and soil permeability. HYSIM requires a two-year ‘warm-up period’; therefore simulated reservoir inflows are used from 1884 onwards. The water resource zone investigated in this study includes three sub-catchments of the River Churnet, one that flows into Tittesworth Reservoir and two that are downstream of the reservoir. Modelled streamflow were validated against observed data prior to this study by Severn Trent Water to ensure simulated streamflow are a good representation. PET data used to extend modelled streamflow are calculated at a monthly time step using the Thornthwaite equation, disaggregated across the month as HYSIM uses a daily time step.

Rainfall data at site A (Figure 4.29), located approximately 4 km south-west of Tittesworth Reservoir and the River Churnet catchment, are used to extend modelled streamflow. Rainfall data at site A and rainfall data used in the baseline assessment are compared using linear regression and double mass analysis. Daily rainfall totals at site A are lower than the rainfall data used in the baseline analysis. The rainfall data used by Severn Trent in the baseline assessment are a combination of individual rain gauges (1918–1958) and Met Office 5 × 5 km gridded rainfall data (1958–2010). The cause of the lower rainfall values at site A is a probable function of altitudinal difference between the location of the rain gauge site A and location of the rain gauges used for the baseline modelling (~100 m a.s.l.), as such a modification factor ($y = 1.13x + 0.486$), where y = site A data and x = 1920–2010 baseline rainfall, was applied to site A. This ensured data consistency between baseline modelling and the extended modelling period, e.g. any observed changes in DO (yield) are not as a result of rainfall inconsistencies between periods.

Water supply system modelling

Aquator is a complex water resource systems model used to simulate the entire water supply network, including riverflows, reservoir storage levels, reservoir compensation flows and water demand (www.oxscisoft.com/). The modelling assists water resource management decisions, including DO (yield) and levels of service (the frequency that a water company places water use restrictions on consumers). The model simulates daily reservoir storage based on inflows derived through rainfall–runoff modelling (HYSIM) and outflows based on assumed demand and compensation flows. Within the study, modelled reservoir storage is used to assess the implications of past drought events on contemporary water resources. DO is calculated for each water resource zone, with demand increased incrementally until supply failure occurs or more than three water use restrictions are introduced (the levels of service frequency set by Severn Trent Water); DO is considered to be the penultimate demand amount before a failure of water supplies to meet demand. This study compares a baseline DO figure (1920–2010) to DO for the period 1884–2012. Baseline DOs are calculated for the North Staffordshire WRZ for 1920–2010; DOs are then recalculated using the 1882–2012 data set.

4.4.4 Results

Drought characterisation

The SPI-12 series identify several notable droughts throughout the reconstruction period. Six multi-year severe droughts have been identified, 1887–1889, 1893–1897, 1921–1923, 1933–1935, 1975–1977 and 1995–1997, at all available sites (Figure 4.31). These events are selected for characterisation based on their duration and severity.

1887–1889

This drought period can only be fully characterised at sites A ,D and E, as sites B and C do not extend fully back through this event, with both series starting (January 1887) within this drought (Figure 4.32a). Drought duration ranged from nine (D) to 27 months (A), with peak severity (SPI) at sites A (–3.20) and D (2.14) in January 1888 and the following month at site E (–2.35). Onset and termination timing are variable, with onset in July 1887 (A), October 1887 (D) and November 1888 (E) and termination in June 1888 (D), February 1889 (E) and September 1889 (A). Across the six key droughts identified in the reconstruction, the 1887–1889 event ranks as one of the longest and most severe droughts at site A (Table 4.5).

1892–1897

The drought event is part of a series of droughts that occurred as part of the 'long drought' (1890–1910) described as a series of drought periods punctuated by wet spells (Marsh et al. 2007); with the period 1892–1897 identified as a particularly severe phase (Figure 4.32b). Across the study region, this drought can be characterised as a long duration, moderate event compared to the other events discussed; minimum SPI values varied from –1.3 (D) to –2.26 (E). The number of months considered to be in 'extreme drought' (SPI – 2.00) ranges from none to four months, which is the lowest count in the droughts characterised. At sites B, D and E, the drought was punctuated by a 'moderately wet' phase in 1894–1895, which is not identified in the SPI series for sites A and C. This means drought duration at sites B, D and E is recorded in two phases between 1892–1894 and 1895–1897. Duration at sites A and C is 43 and 52 months respectively, the longest droughts identified in the reconstruction. Timing of onset occurred in two phases between November and December 1892 at sites C, D and E and a second onset phase between July and October 1893 at sites A and B. However, timing of termination appears coherent across the region between February and March 1897. The drought was most severe at site C with the longest duration and most months in 'extreme drought'.

1921-1923

Drought duration varied across the region (Figure 4.32c). Sites B (34) and E (30) experienced the longest events (months), with sites A (14) and C (12) the shortest droughts (months). Each site recorded minimum SPI values below –2.00, classified as an extreme drought, ranging in intensity from –3.95 (B) to –2.36 (A). Drought onset occurred between January (B) and May (A) 1921, with onset at sites C, D and E all occurring in April 1921. Termination occurred in two phases, April to June 1922 at sites A and C and September to November 1923 at sites B, D and E. This drought includes the lowest SPI value (–3.95 at site B) across all sites for the entire reconstruction period, suggesting that the event was a particularly acute drought for some parts of the region.

1933-1935

Drought onset occurred between August and September 1933 at sites A, B, D and E, occurring later at site C in February 1934 (Figure 4.32d). The drought continued and peaked throughout 1934, terminating in 1935 starting in February (E), June (D), October (A and B) and lastly in November (C). Drought duration ranged from 17 (E) to 27 months (B). Peak severity ranged from –3.47 (D) to –2.21 (C). Sites A and B display a very similar drought structure in onset, termination and number of months (10) in extreme drought (SPI <–2.00).

1975-1977

Drought onset occurred in late 1975 from October (B, C, D), November (A) to December (E); with peak severity occurring in July (D) and August 1976 (A, B, C, E) (Figure 4.32e). Drought severity lessened from September 1976, with termination coherent across sites A, B, C and D in February 1977, whilst the drought continued at site E until August 1977. Drought duration ranged from between 16 and 17 months at sites A, B, C and D to 23 months at site E. The drought of 1975–1977 was the most severe in the series at sites C and E.

1995–1997

Drought onset occurred from late 1995 (B, C, D) into early 1996 (A, E) with the drought worsening throughout summer 1996 (Figure 4.32f). By November 1996 severity had begun to reduce at all sites, although drought conditions persisted and continued throughout 1997, with termination coherent across the region in January 1998. Drought duration ranged from 21 (B) to 28 months (D) with months in extreme drought ranging from 0 (E) to 10 months (B) and peak severity ranged from –2.67 (C) to –1.51 (E).

Drought events appear to be spatially coherent across the region; inter-station correlation analysis between the SPI values reveals a high level of statistically significant correlation between sites (Table 4.7), influenced by the distance between sites. The strongest relationship is between sites C and D with a correlation coefficient at 0.85; the weakest correlation (0.68) is between sites B and E, the sites furthest apart. Despite the high levels of spatial coherence there are apparent variations in drought structure across the region, particularly in peak severity (minimum SPI value) and months in extreme drought. Within each drought event peak severity was variable by at least 1 SPI drought intensity classification, for example, peak severity across sites A–E during the 1995–1997 drought peak severity ranged from –2.67 at site C to – 1.51 at site E.

Analysis of drought characteristics shows that the pre- 1920 droughts (1887–1889, 1892–1897) are significant drought events in terms of severity and duration. At site A the 1887–1889 event includes the lowest SPI-12 value recorded (–3.20) and the second longest drought duration (27 months) over a 125 year period. The 1892–1897 drought ranks as the longest drought at site A (43 months) and C (52 months). Each drought has a unique set of characteristics and impacts (Wilhite & Svoboda, 2000); therefore, it would be beneficial to use an extended modelling period to investigate if DO is changed and test the robustness of the current modelling period used in water resource management and drought plans.

Table 4.6: Key drought characteristics for notable drought events

Drought Event	Site	Drought Duration (months)	Months in Extreme Drought	Peak Severity	Onset (mm/yyyy)	Termination (mm/yyyy)
1887-1889	A	27	7	-3.20	07/1887	09/1889
	B	21	8	-2.95	10/1887	04/1889
	C*					
	D	9	1	-2.14	10/1887	07/1888
	E	15	5	-2.35	11/1888	02/1889
1892-1897	A	43	1	-2.01	07/1893	02/1897
	B	6[p1] 20[p2]	0	-1.57	10/1893	02/1897
	C	52	4	-2.15	11/1892	03/1897
	D	23[p1] 9[p2]	0	-1.30	12/1892	02/1897
	E	15[p1] 19[p2]	2	-2.26	12/1892	03/1897
1921-1923	A	14	4	-2.36	05/1921	06/1922
	B	34	12	-3.95	01/1921	11/1923
	C	12	1	-2.47	04/1921	04/1922
	D	21	8	-2.93	04/1921	10/1923
	E	30	6	-2.69	04/1921	09/1923
1933-1935	A	25	10	-3.10	09/1933	10/1935
	B	27	10	-2.60	08/1933	11/1935
	C	20	1	-2.21	02/1934	10/1935
	D	22	14	-3.43	08/1933	06/1935
	E	17	9	-3.03	09/1933	02/1935
1975-1977	A	16	1	-2.31	11/1975	02/1977
	B	17	6	-2.67	10/1975	02/1977
	C	17	10	-3.31	10/1975	02/1977
	D	16	7	-3.14	10/1975	02/1977
	E	23	13	-3.30	12/1975	08/1977
1995-1997	A	24	7	-2.34	01/1996	01/1998
	B	21	10	-2.52	11/1995	01/1998
	C	26	8	-2.67	11/1995	01/1998
	D	28	3	-2.18	09/1995	01/1998
	E	23	0	-1.51	02/1996	01/1998

*Start of rainfall record began during 1887 drought [p1] Phase 1 [p2] Phase 2

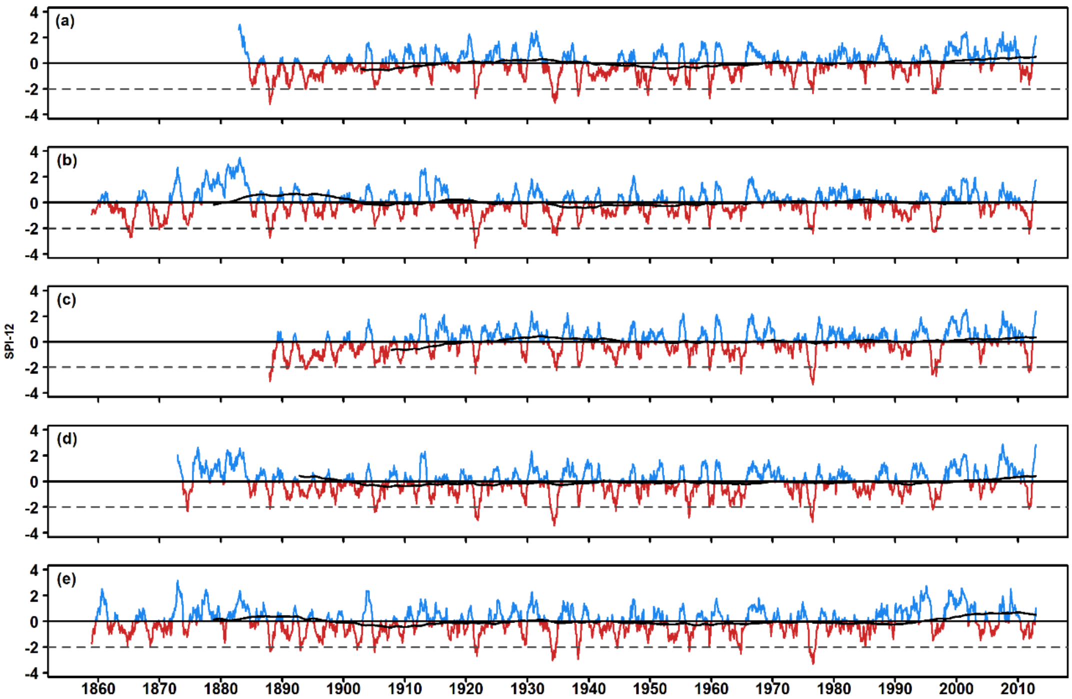

Figure 4.32: SPI-12 series for sites A-E for the entire length of rainfall record, dashed line indicates extreme drought

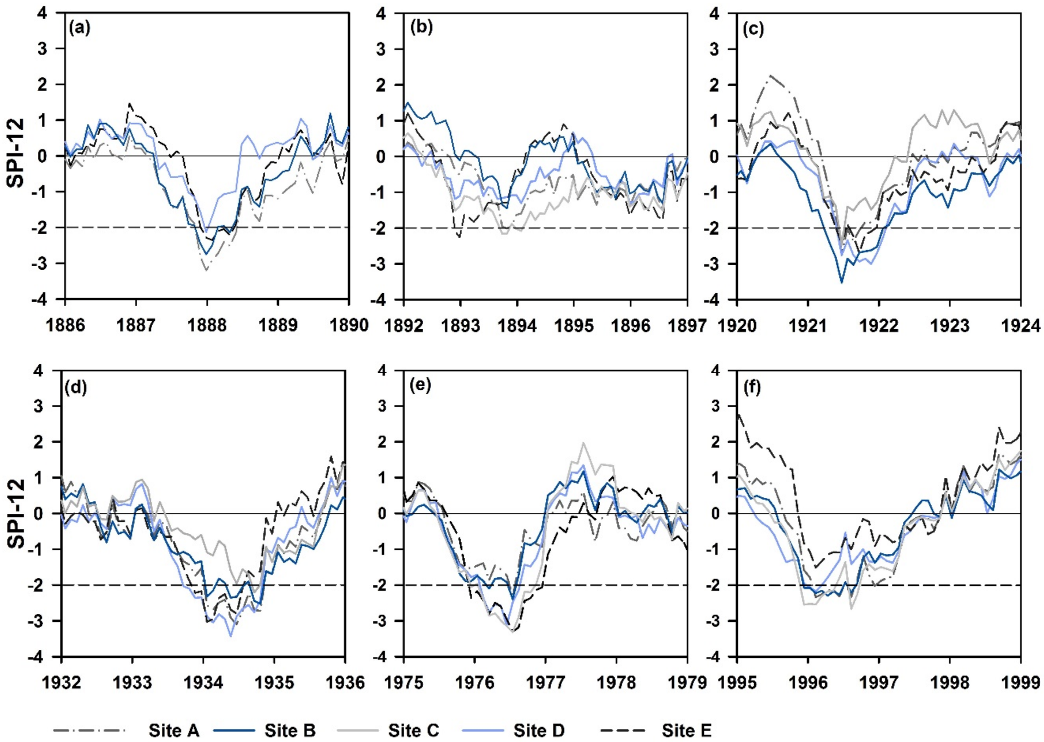

Figure 4.31: SPI-12 series site A-E for drought periods (a) 1887-1889, (b) 1892-1897, (c) 1921-1923, (d) 1933-1935, (e) 1975-1977, (f) 1995-1997, dashed lined indicates extreme drought

Water Resource Modelling and assessment of DO

DO calculated for the NSWRZ using the extended reservoir inflow data equates to 152 Ml/d, with a baseline DO for the period 1920–2010 calculated at 153 Ml/d. The baseline DO calculated within this study is 3 Ml/d higher than DO value reported for the North Staffordshire WRZ reported in the Severn Trent Water WRMP (Severn Trent Water 2014a). Baseline DO (1920–2010) for this study had to be re-calculated due to modelling constraints within the water resources model. Inclusion of the 1884–2012 data reduces DO by 0.65%, making no significant difference to the supply and demand balance of the water resource zone. The critical drought for the water resource zone remains the 1933–1935 event, as stated in the water company drought plan (Severn Trent Water 2014b). However, it is beneficial to investigate the impact of the pre-1920 droughts on modelled reservoir storage.

Figure 4.33 shows simulated reservoir levels for the most severe droughts during the 1884–2012 modelling period plotted with drought trigger curves. Drought trigger curves are a common drought measure used by decision makers to identify when management actions should be activated (Watts et al. 2012). The drought trigger curves, developed by Severn Trent Water (2014b), are used in conjunction with a suite of indicators to monitor drought conditions, with each trigger threshold resulting in the implementation of a defined set of management actions. Trigger curves C, D and E (Figure 4.33), all indicate increasing degrees of below normal storage levels, with trigger F indicating exceptionally low storage compared to the seasonal norm. The Severn Trent Water Drought Plan (Severn Trent Water 2014b) includes an assessment of the frequency of modelled storage at Tittesworth Reservoir crossing drought triggers D and E, which would typically lead to changes in demand and supply-side management changes and/or restrictions.

Modelled storage of the 1887–1889 drought (Figure 4.33a) reaches a minimum of 52% during August 1887, which is below normal storage levels; management actions at this storage level include raising increased awareness of a potential drought situation. The SPI characterisation would suggest that this drought may have similar impacts on reservoir storage to the 1933–1935 event; however, the impacts of the 1887–1889 event are less severe. The 1893–1897 drought exhibits a more severe response on modelled reservoir storage than the 1887–1889 event. Drought trigger D is crossed in both 1893 and 1894, with minimum reservoir levels of 41% in October 1894. Drought Trigger D is associated with a number of supply-side management options and demand management actions that include increased public awareness of a drought situation and water saving measures. Trigger E is associated with the implementation of water use restrictions, e.g. temporary use ban (hosepipe bans).

Table 4.7: Inter-station correlation SPI-12 1887-2012 (using Pearson's r)

Site	A	B	C	D	E
A					
B	0.78				
C	0.78	0.78			
D	0.77	0.78	0.85		
E	0.73	0.68	0.71	0.71	

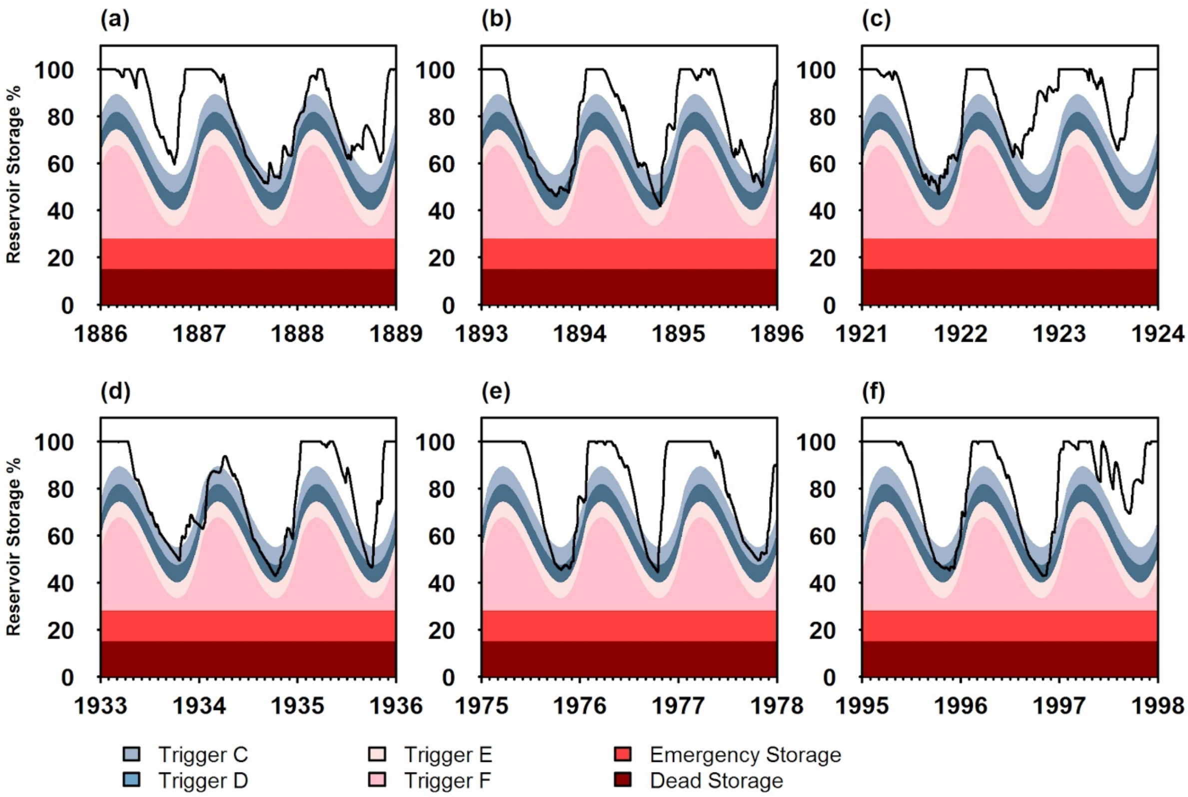

Figure 4.33: Simulated reservoir levels and drought trigger curves for characterised drought periods (a) 1887-1889, (b) 1892-1897, (c) 1921-1923, (d) 1933-1935, (e) 1975-1977, (f) 1995-1997

4.4.5 Discussion

Impact of pre-1920 drought on reservoir storage

The pre-1920s reconstruction includes two notable drought events (1887–1889 and 1893–1897). These droughts rank highly in terms of severity and duration across the NSWRZ. Analysis of the meteorological drought characteristics and application of a long rainfall series indicates that the most severe meteorological droughts are not necessarily the worst water resource droughts. To understand further the relationship between meteorological drought and hydrological drought in a water resource system it is necessary to investigate how the drought characteristics have varying impacts on modelled reservoir levels. The drought characterisation indicates the 1887–1889 and 1933–1935 events have similar drought structures, but the 1887–1889 drought is more severe in terms of maximum severity (SPI –3.2) and drought duration (27 months) than the 1933– 1935 benchmark drought, but that the 1933–1935 drought has greater impact on simulated reservoir levels (Figure 4.33), potentially as a result of antecedent conditions prior to drought onset. During the six months preceding the 1887– 1889 drought SPI-12 values are higher than SPI-12 values of the six months preceding the 1933–1935 drought, highlighting the importance of antecedent conditions in the formation of drought.

The comparison between characteristics of the 1887–1889 and 1933–1935 droughts indicates that wetter phases within a drought have a significant impact on reservoir storage, as the 1887–1889 drought shows a rapid decrease in SPI severity between June (SPI-12 –2.2) and July (SPI-12 –1.2) 1888, with a corresponding increase in simulated reservoir storage between August and September 1888 (Figure 4.33a). The difference between modelled reservoir storage in the winter months of the two droughts (1887–1889 and 1933–1935) identifies winter reservoir recharge remains ‘below’ normal throughout winter (1933–1934) exacerbating the drought impact during summer 1934; in contrast the simulated reservoir storage during the winter months of 1887–1888 shows full recovery of the reservoir storage (to 100%).

The 1892–1897 drought event sits within the 1890–1910 ‘Long Drought’. At site A the 1892–1897 drought ranks as the longest duration event (43 months) in the reconstruction record; it can be considered a long duration moderate event. However, the impact of this drought on modelled reservoir storage leads to sustained below normal seasonal reservoir levels throughout 1893 and the summer months of 1894 (Figure 4.33b). The long-term nature of multiple years below normal can be seen within the long SPI series (Figure 4.32 d and e). Whilst these illustrate that the period is notable within the long timeframe of the study as a prolonged period of drier than normal conditions, it does not present a high degree of severity, complementing the findings of Marsh et al. (2007).

Implications for water resource modelling

The evidence from this study indicates that within the WRZ the use of the 1933–1935 drought as a benchmark event is appropriate. Whilst other droughts have been of comparable severity (e.g. 1921–1923; 1975–1977), they have lacked the impact of the 1933–1935 event (more months in extreme drought than any other across all stations considered – 44 months). Whilst this study has only examined one WRZ, it would be beneficial to use this approach across a whole water supply region to understand fully the impact of historic droughts on the water resource system. This may be particularly beneficial if the same events are impacting with similar severity across all WRZs, then water resource management is more challenging, but if spatial variability exists then transfers between WRZs may help to mitigate the impacts of drought on water resources. This study indicates that the inclusion of the extended record has little impact on DO calculations, supporting the findings of Spraggs et al. (2015). However, both Spraggs and Wade et al. (2006) note that further extension of the series back to the early nineteenth century results in more severe droughts being included, which impact water resources; so whilst the extension of the series (1880s–1918) provides little modification of DO, further extension potentially incorporating more severe droughts may have significant implications for water resources. The length of extension may come with the caveat of the past potentially being less representative of the current, very long extensions, e.g. Todd et al. (2013) back to the seventeenth century, identifies a number of very severe droughts, comparable or worse than those within existing records, in a period generally considered as wetter and cooler (Lamb, 1995), highlighting the need for additional understanding of drought characterisation. The most severe droughts span multiple seasons, with most incorporating single if not multiple years of incomplete winter recharge of reservoirs. This poses a considerable challenge when mitigating the impacts of future intensification of the hydrological cycle and associated changes in water supply and demand arising from predicted climate change. Considerable uncertainty exists concerning how future climate changes may impact drought development and propagation, as considerable uncertainty exists in current climate model projections for extremes (Watts et al., 2015). The identification of the importance of antecedent conditions in the formation of the drought supports the finding of Todd et al. (2013) when examining the most severe droughts.

Whilst meteorological drought indicators are a valuable tool, particularly for event monitoring and onset, they currently offer little information on drought impacts across a water resource system. Understanding the link between meteorological and hydrological drought is vital for the application of drought indices in water resource management where the impact of a drought is a function of a number of factors including climate, catchment characteristics, drought characteristics, water demand and antecedent conditions. Further work is required to explore the link between meteorological drought and hydrological drought, particularly links between meteorological drought indices, streamflow, groundwater and water supply systems.

4.4.6 Conclusions

This paper presents an application of the SPI for operational water resources management and an attempt to physically link meteorological drought indices to water resources in the form of modelled reservoir levels at a long timescale. Meteorological drought indices can provide valuable information on drought structure as part of a suite of drought indicators and management tools. Spatial analysis of drought characteristics across the study area indicates a high level of regional spatial coherence of drought. However, sub-regional variations in drought structure exist, particularly in peak severity and months in extreme drought. These variations highlight the importance of regional scale drought studies for research at the water resource management level. Multi-year droughts are a recurring feature of the UK climate, each with a unique set of characteristics; a better understanding of UK drought character offered by the long series provides an insight for water resource management and drought planning.

4.5 Sub-regionalisation of rainfall and meteorological drought in the STR

Whilst *Chapter 4 identifies intra-regional variability of meteorological drought characteristics across the STR, further examination of the spatial and temporal coherence requires greater spatial coverage of rainfall data. This is addressed with additional rainfall records allowing analysis at 15 sites from 1962-2012.*

Whilst there appears to be a high level of spatial coherence of meteorological droughts based on correlation analysis (sections 4.2 and 4.3), there is intra-regional variability in drought characteristics particularly onset, duration and termination. To examine further the intra-regional variation of meteorological droughts, the STR is analysed at a sub-regional level. The identification of sub-regional clusters may be beneficial for drought monitoring in operational water resource management particularly in understanding potential drought impacts in individual water resource zones

4.5.1 Spatial Variability of Rainfall

The STR sits within two UK regional climates, Wales and the Midlands (see Chapter 3). The spatial distribution of rainfall in the Midlands is described as transitional between the wetter west and drier east (Phillips, 2013). To explore the influence of this on droughts within the STR further, principle component analysis (PCA) is used to sub-regionalise rainfall in the STR using monthly rainfall data for the period 1962-2012 for 15 sites. An S-mode (data matrix contains rainfall stations as columns and monthly observations as rows) correlation based PCA with varimax orthogonal rotation is used, based on the methods of Gocic and Trajokic (2014). S-mode PCA is commonly used in atmospheric sciences to explore the joint space/time variations of a variable of interest (Wilks, 2011). To assess whether the monthly rainfall data is suitable for PCA the Kaiser-Meyer-Olkin (KOM) measure of sampling adequacy is used; the KMO value in this case is 0.9 indicating that the rainfall data to suitable for PCA (Martins, 2012).

A scree plot of the eigenvalues for each principle component and North's rule of thumb (North et al., 1982) suggest that the first two principle components should be retained. Rotated principle components 1(RPC-1) and 2 (RPC-2) explain 85% of total variation, accounting for 48% and 37% respectively. Varimax rotation is used to obtain more spatially localised and uncorrelated principle components (Von Storch and Zwiers, 1999). A loadings plot of RPC-1 and RPC-2 (Figure 4.34c) for the 15 rainfall sites and mapped loadings of RPC-1 and RPC-2 identify highest loading values (>0.8) for RPC-1 in the east and lowest loading values (<0.42) in the west of the STR (Figure 4.34a); RPC-1 is representative of the east of the STR. RPC-2 loading values are highest (>0.8) in the west and lowest (<0.42) in the east of the STR (Figure 4.34b); RPC-2 is representative of the far west of the STR. Both RPC-1 and RPC-2 loading values for the rainfall sites in the centre of the STR sit between 0.42-0.80. The mapped loadings patterns suggests there are three sub-regional clusters in the STR. These clusters reflect the spatial distribution of higher rainfall totals in the west that decrease in an eastwards direction as described by Phillips (2013).

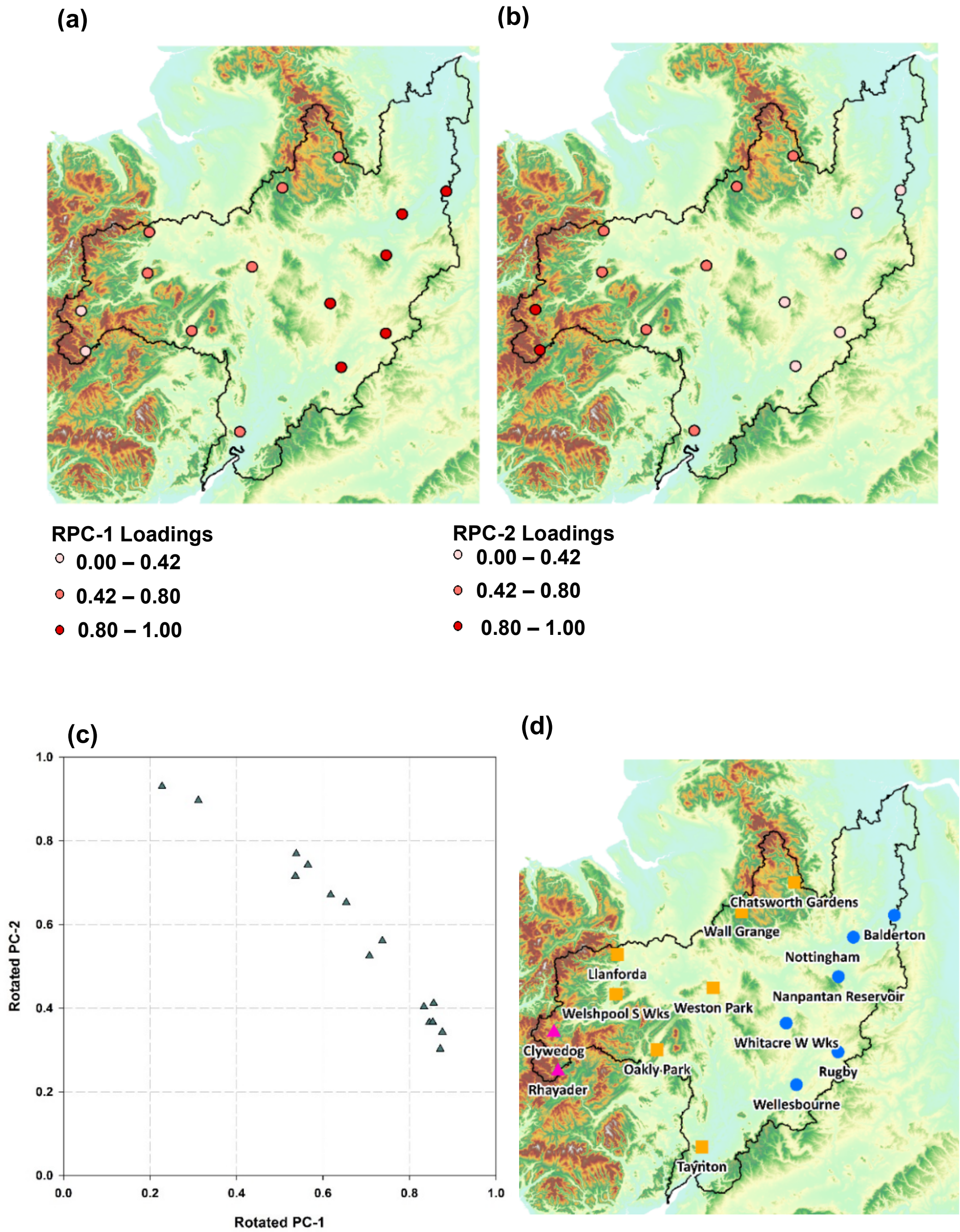

Figure 4.34: Rotated PCA results for monthly rainfall (a) mapped RPC-1 loadings, (b) mapped RPC-2 loadings, (c) RPC-1 and RPC-2 loadings plot, (d) map of rainfall sub-regional clusters

4.6 Spatial Variability of Meteorological Drought

To investigate drought variability, S-mode PCA with varimax rotation is used to assess whether the STR can be divided into sub-regions based on the SPI at 1- 3-, 6-, 9 and 12-month accumulation periods. PCA is used in a number of studies to investigate spatial and temporal variability of droughts (Bonaccorso et al., 2003; Vicente-Serrano and Cuadrat-Prats, 2007, Santos et al., 2010; Martins et al., 2012). As with the rainfall PCA, scree plots and North's rule of thumb (North et al., 1982) suggests the first two principle components should be retained.

The variance of the first two rotated principle components for each SPI timescale are presented in Table 4.8. In all cases RPC-1 and RPC-2 account for >83% of the total variance, the highest being 85.6% for SPI-1 and the lowest 83.1% for SPI-9. As the SPI accumulation period is increased RPC-1 accounts for a greater percentage of total variance. RPC-2 accounts for between 24.4% (SPI-12) and 36.6% (SPI-1), the percentage of variance explained by RPC-2 decreases as the SPI accumulation period is increased. The increased variance captured by RPC-1 at longer accumulation periods is evident in loadings plots for RPC-1 and RPC-2 for each SPI accumulation period (Figure 4.35). The loadings plots for monthly rainfall data and the SPI-1 show similar loading values. However, as the SPI accumulation periods increase, the loading values for sites identified in cluster 2 in the rotated PCA of monthly rainfall totals have increased for RPC-1 and decreased loading values for RPC-2.

Table 4.8: Explained variance (%) of RPC-1 and RPC-2 loadings for SPI accumulations periods 1-, 3-, 6-, 9 and 12-months

Rotated Principle Components	SPI-1	SPI-3	SPI-6	SPI-9	SPI-12
RPC-1	49.0	53.4	57.2	58.5	59.0
RPC-2	36.6	30.8	26.1	24.6	24.4
Cumulative	85.6	84.2	83.3	83.1	83.4

Mapped loadings of RPC-1 and RPC-2 for SPI-1 (Figure 4.36) show a similar pattern to the mapped rainfall loadings; however, as the SPI accumulation period increases this three cluster sub-regional pattern breaks down. This breakdown in sub-regional patterning at longer timescales is a result of reduced variability of the SPI when summed over longer (>

6-months) accumulation periods. This suggests that meteorological droughts in the STR operate in two sub-regional clusters. The first cluster includes rainfall sites Rhayader and Clwedog in the far west of the region and the remaining 13 rainfall sites in the STR form the second cluster (Figure 4.37).

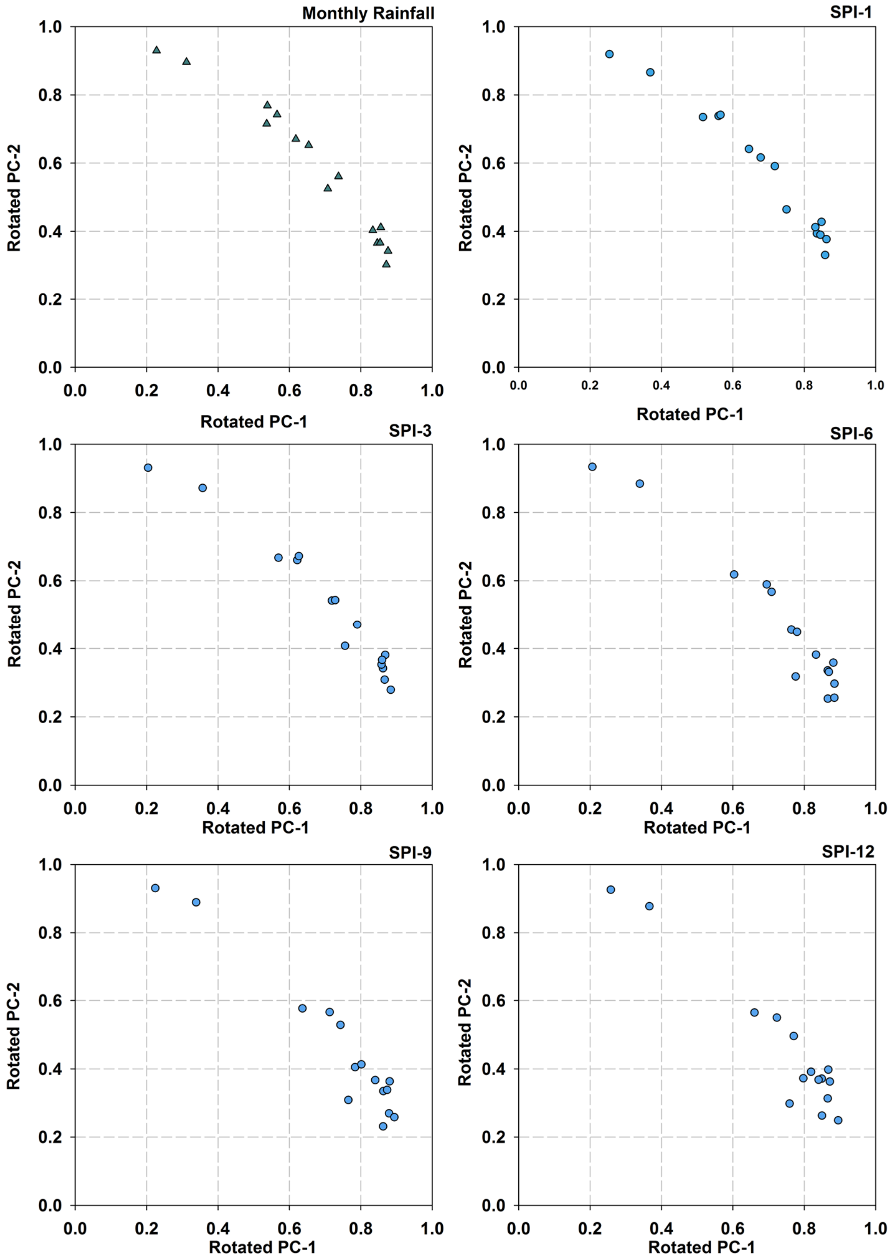

Figure 4.35: Loadings plots for RPC-1 and RPC-2 for monthly rainfall and SPI at 1-, 3-, 6-, 9- and 12-month accumulation periods

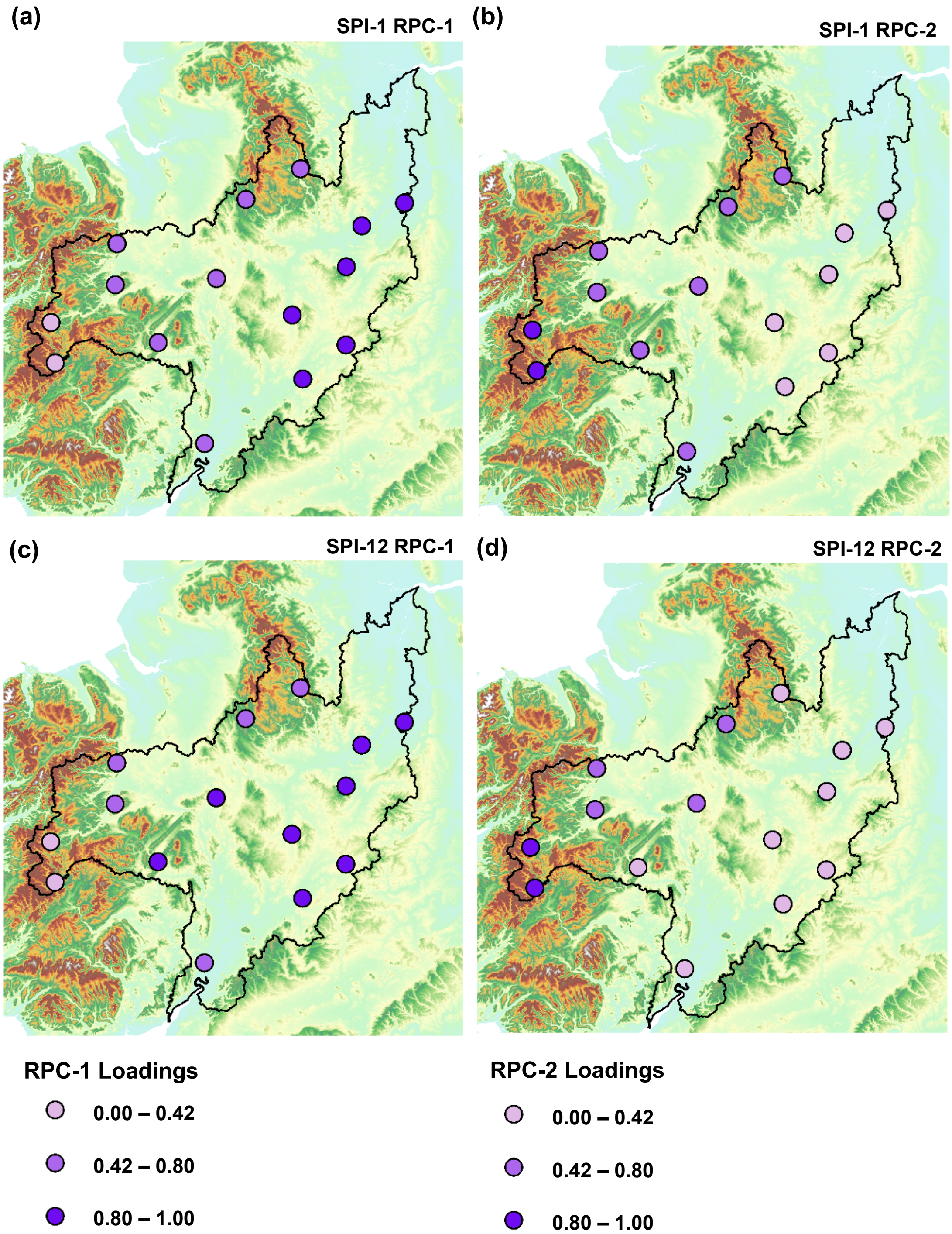

Figure 4.36: Mapped rotated principle component loadings for (a) RPC-1 SPI-1, (b) RPC-2 SPI-1, (c) RPC-1 SPI-12, (d) RPC-2 SPI-12

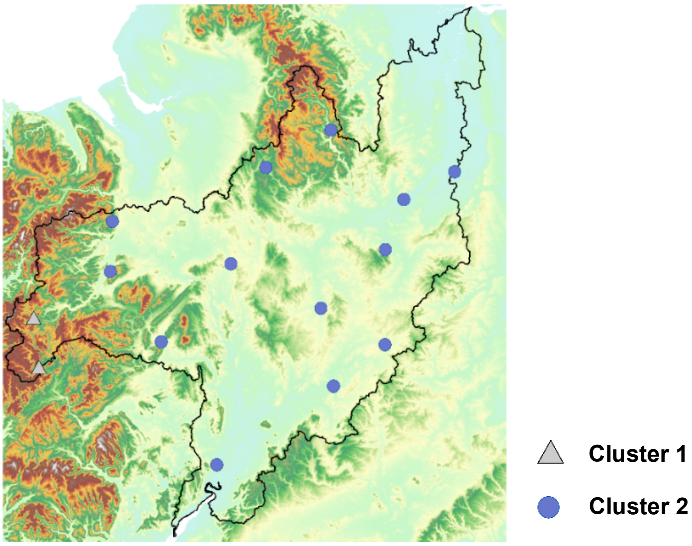

Figure 4.37: Sub-regional drought clusters

To examine the variation between drought clusters 1 and 2, SPI-12 series for each of the clusters is calculated using the mean rainfall of the sites within the clusters (Figure 4.38). This highlights both similarity and variability in drought behaviour between the clusters. For example, onset and peak severity of the 1975-77 drought appears coherent between clusters, but drought termination is variable occurring later in cluster 1. To further investigate the similarities and differences between the clusters heat maps (Figures 4.39 – 4.43) are used for five drought events between 1962 and 2012 (1962-65, 1975-77, 1990-92, 1995-97 and 2010-12) based on the SPI-12. For each drought, two heat maps are produced, one for the sub-regional drought clusters and one for all 15 rainfall records used throughout this thesis. In the heat maps displaying each of the 15 rainfall records, the sites are ordered by longitude from west to east reflecting the west to east rainfall gradient across the STR.

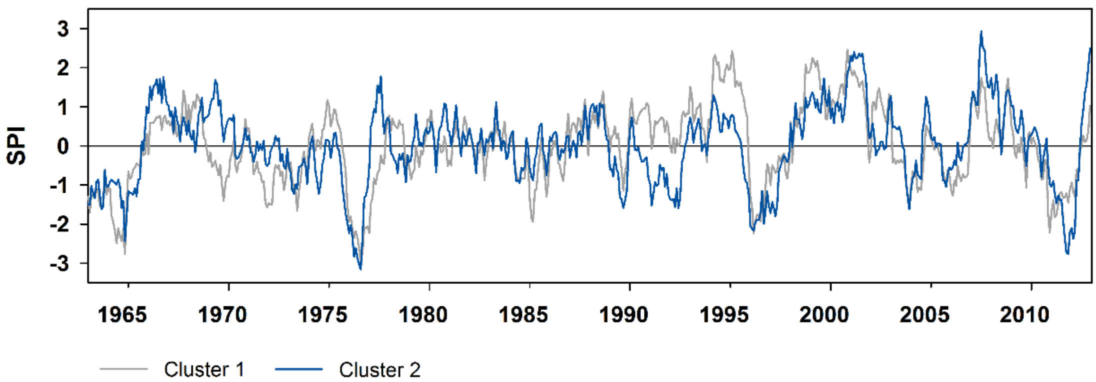

Figure 4.38: SPI-12 series for sub-regional drought clusters (1962-2012)

4.6.1 Spatial and Temporal Variability of the 1962-65 Drought

The 1962-65 drought is characterised as a long duration moderate severity drought (section 4.2.12). Between January 1963 and February 1964, drought behaviour across the STR appears coherent; however, from March 1964 there is increased variability between Cluster 1 and Cluster 2 (Figure 4.39a). Variability of drought onset cannot be examined for this event as the analysis starts within the drought, the first SPI-12 value starts in December 1962. The site heatmap (Figure 4.39b) shows greater intra-regional variation, from March to August 1964, sites in the east show increasing SPI values whilst Clywedog, Rhayader, Llanforda and Welshpool in the west are decreasing; this pattern is evident in both the cluster and site heat maps. Between September and November 1964 there is less intra-regional variability, with SPI values decreasing and peak severity occurring in November at all sites. From December 1964 SPI values increase across the STR but drought termination is highly variable particularly at sites in the west (Clywedog, Rhayader, Welshpool, Llanforda and Oakly Park) ranging from June 1965 at Welshpool to February 1966 at Oakly Park. In the centre, north and east of the STR drought termination occurs in September 1965 (Wall Grange, Whitacre, Chatsworth, Wellesbourne, Rugby and Nanpantan) and November (1965 Weston Park, Nottingham and Balderton).

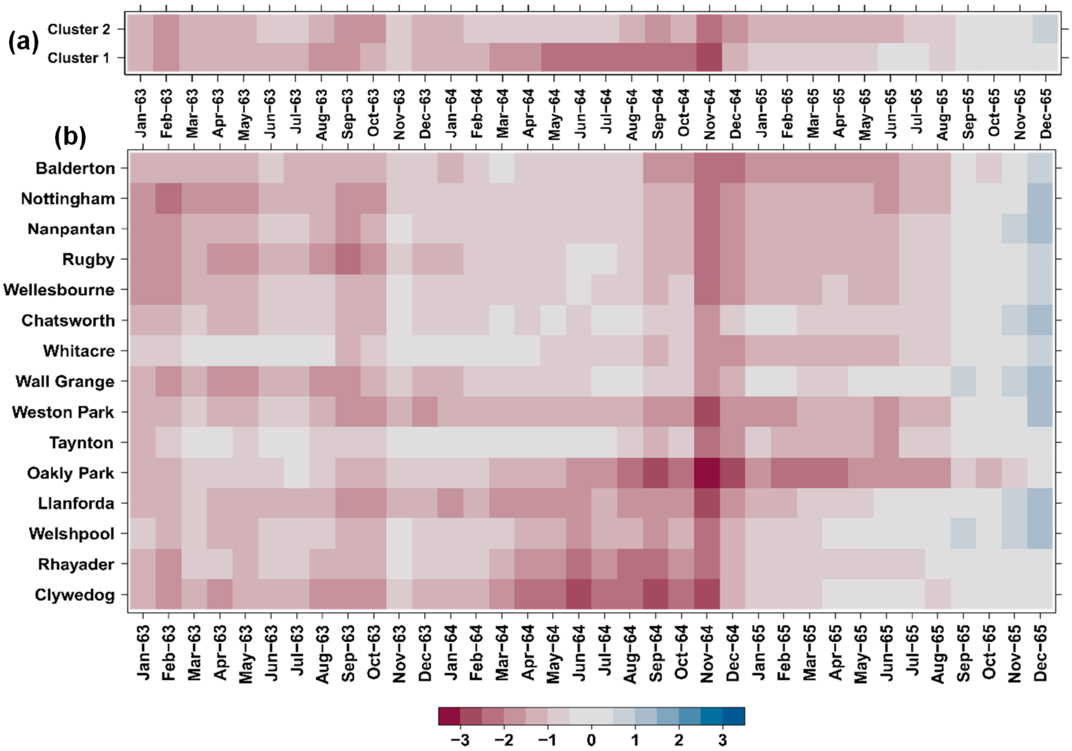

Figure 4.39: Heatmaps of SPI-12 reconstruction for the 1962-65 drought (a) drought clusters, (b) individual rainfall records

4.6.2 Spatial and Temporal Variability of the 1975-77 Drought

Based on the cluster heatmap (Figure 4.40a), onset and termination of the 1975-77 drought is variable between the clusters. Drought onset occurs first in Cluster 2 (September 1975) and followed by Cluster 1 (December 1975), event termination also occurs first in Cluster 2 (Febuary 1977) and second in Cluster 1 (August 1977). The site heatmap (Figure 4.40b) identifies some variability in drought onset within Cluster 2, between September and November 1975. At both Rhayader and Clywedog in Cluster 2, drought onset occurs in December. Within Cluster 2 drought termination varies between December 1976 (Oakly Park) and April 1977 (Wall Grange), however, at 8 of 13 sites in Cluster 2 termination occurs in February 1977. At sites within Cluster 1 drought termination occurs at Rhayader in August 1977 and at Clywedog in October 1977. The timing of peak drought severity and drought classification is coherent across the STR, in July and August 1976 the whole region is in 'extreme drought' with SPI values <-2. SPI values at Rhayader, Chatsworth, Oakly Park, Nanpantan and Balderton reach <-3 during August 1976, indicating a coherence of drought severity across the STR.

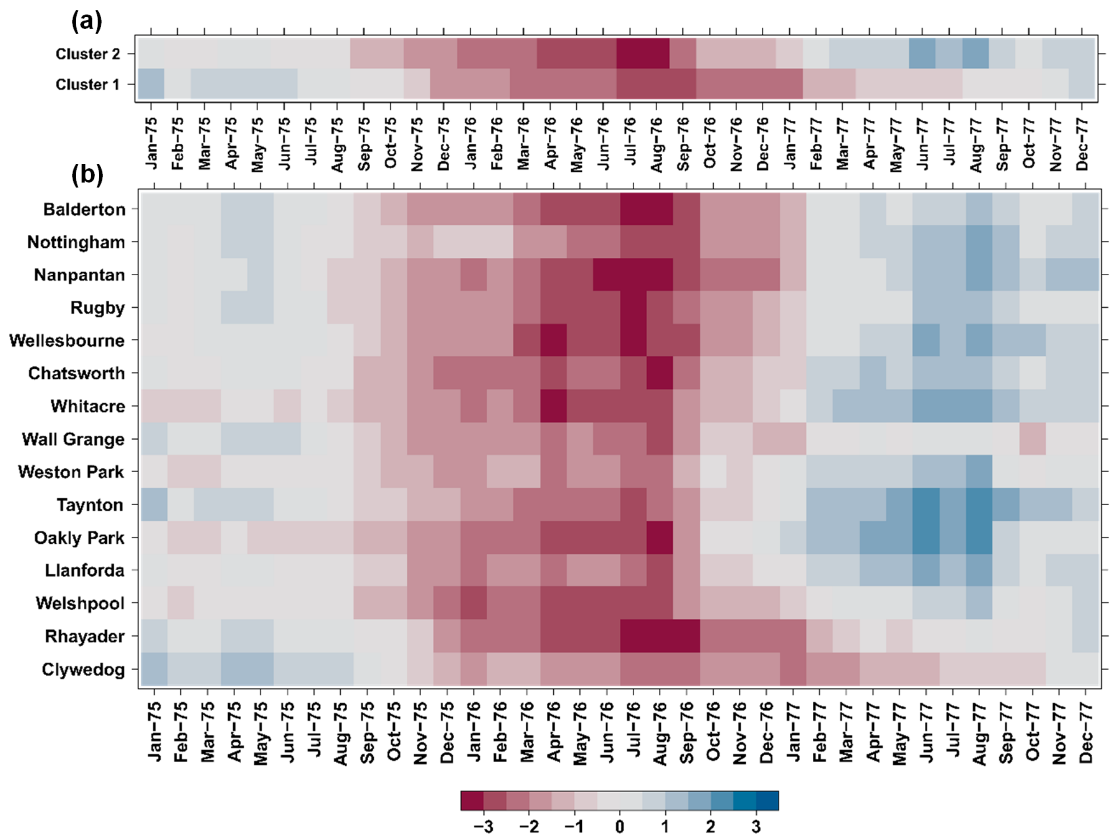

Figure 4.40: Heatmaps of SPI-12 reconstruction for the 1975-77 drought (a) drought clusters, (b) individual rainfall records

4.6.3 Spatial and Temporal Variability of the 1990-92 Drought

The 1962-65 drought is comparable to the 1990-92 drought as its characteristics are a long duration, moderate severity event. However, unlike the 1963-65 drought this event is only observed in Cluster 2 suggesting a lack of spatial coherence in drought behaviour across the STR (Figure 4.41a). Across the 13 sites within Cluster 2 there is considerable variability in drought characteristics; onset is particularly varied ranging from July 1990 at Chatsworth to February 1992 at Welshpool (Figure 4.41b). Unlike most other droughts examined throughout Chapters 4 and 5, this event does not have a pronounced timing of peak drought severity and event minimum SPI values vary across three drought severity classifications from -1.3 (moderate drought) at Weston Park to -2.2 (extreme drought) at Llanforda. Drought termination is also variable occurring between August 1992 and January 1993 at all sites excluding Chatsworth where event termination occurs in July 1993.

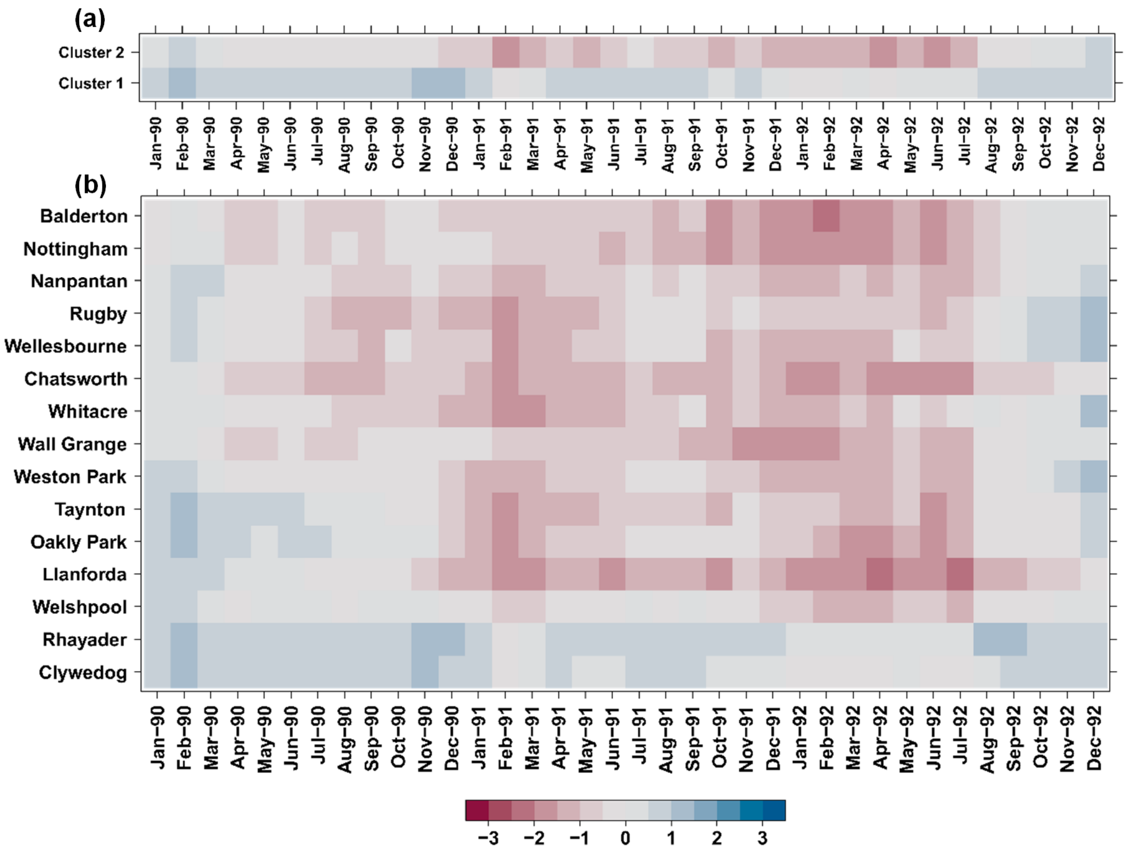

Figure 4.41: Heatmaps of SPI-12 reconstruction for the 1990-92 drought (a) drought clusters, (b) individual rainfall records

4.6.4 Spatial and Temporal Variability of the 1995-97 Drought

Based on Clusters 1 and 2 (Figure 4.42a), there appears to be little variability in the timing of drought onset and termination. Drought onset occurs in December 1995 in Cluster 2 and January 1996 in Cluster 1; termination occurs in January 1998 in both clusters. Between March and August 1996 there appears to a high level of coherence in drought severity with consistent SPI values between the clusters. However, from September 1996 there is an increase in spatial variability between the clusters, Cluster 2 SPI values remain <-1 (mild to moderate drought), whilst SPI values in Cluster 1 range between 0 and -1 (near normal to mild drought conditions). Examination of the site heat map (Figure 4.42b) identifies variability between the sites within each cluster. Rhayader and Clywedog in Cluster 1 have coherence in the timing of drought onset and termination but not drought severity. Between March 1996 and January 1997 this event is more severe at Clywedog by two drought classification categories e.g. moderate drought at Rhayader and extreme drought at Clywedog. The drought is least severe at Rhayder, Taynton and Oakly Park, in the west and south-west of the STR and most severe at Wall Grange and Chatsworth in the north of the STR.

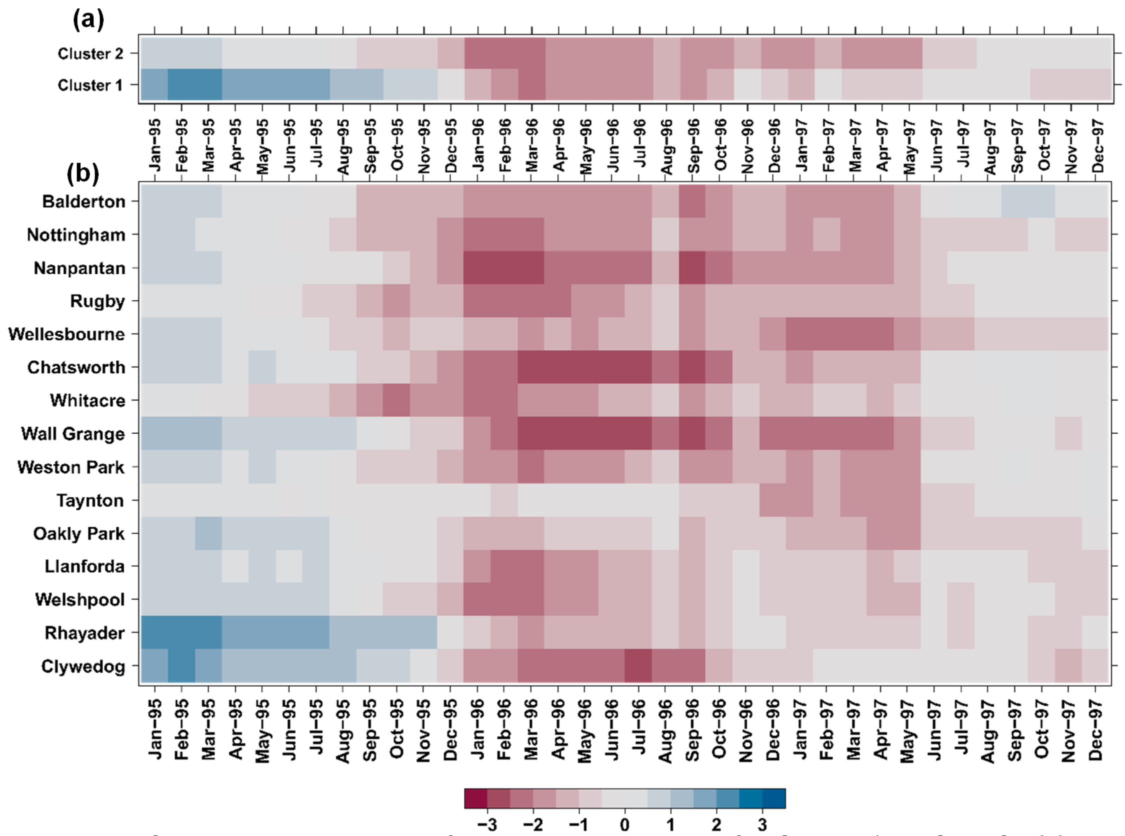

Figure 4.42: Heatmaps of SPI-12 reconstruction for the 1995-97 drought (a) drought clusters, (b) individual rainfall records

4.6.5 Spatial and Temporal Variability of the 2010-12 Drought

Based on the drought clusters (Figure 4.43a), onset occurs first in Cluster 1 (November 2010) followed by Cluster 2 (January 2011). However, examination of the site heatmap (Figure 4.43b) shows drought onset across the STR exhibits strong intra-regional variation, occurring in the three spatially distinct groups. These onset phases are; (1) Weston Park, Wall Grange and Whitacre in the centre and north of the STR (June and July 2010), (2) Clywedog, Rhayader, Welshpool Llanforda and Oakly Park in the west of the STR (November and December 2010) and (3) Chatsworth, Wellesbourne, Nanpantan, Rugby, Nottingham and Balderton in the north and the east of the STR (March to August 2011). This suggests a crude north-west to south-east gradient in drought onset. However, drought onset at Taynton, in the south-west of the STR, also occurs within the third group. At Rhayader and Clywedog peak drought severity occurs in December 2010 (based on both cluster and site heatmaps) at all other sites across the STR it occurs in October and November 2011. This highlights the lack of coherence in drought severity between Cluster 1 and Cluster 2. Unlike drought onset and peak severity, event termination appears coherent across the STR occurring between June and August across all sites excluding Rhayader.

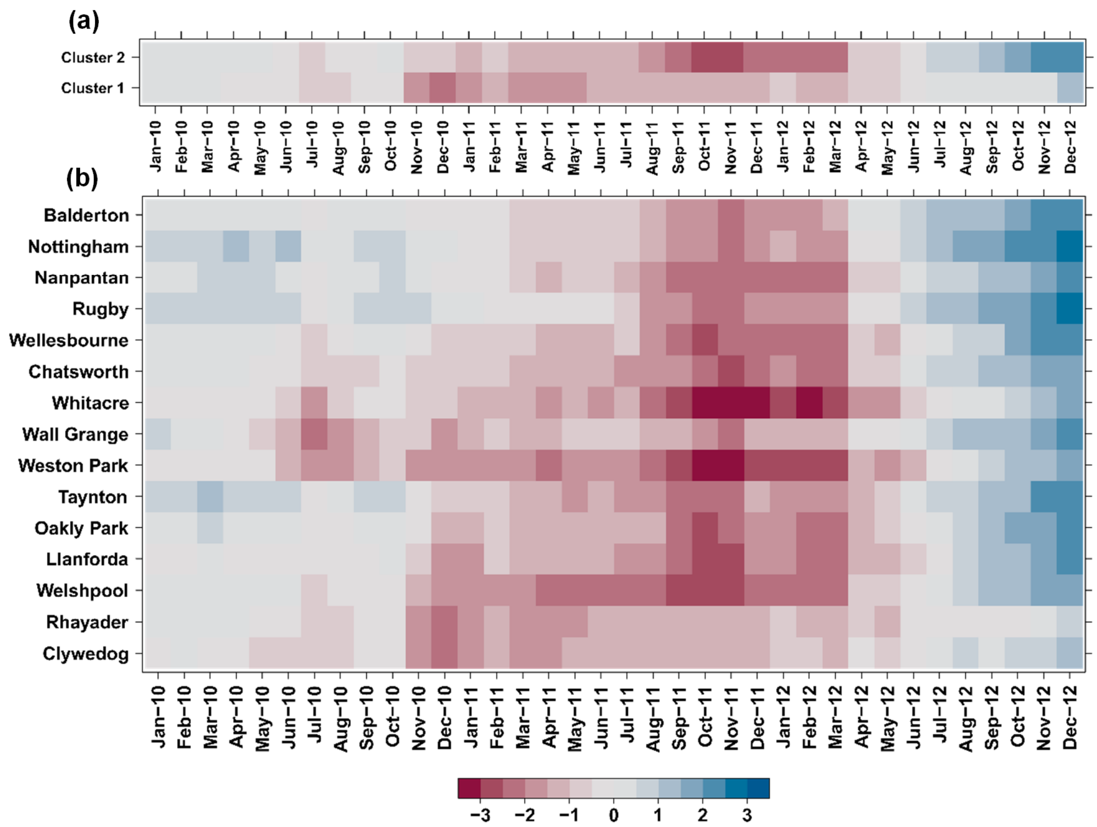

Figure 4.43: Heatmaps of SPI-12 reconstruction for the 2010-12 drought (a) drought clusters, (b) individual rainfall records

4.7 Summary

The results presented in this chapter identify numerous droughts with durations greater than 10-months in the STR between 1858 and 2012. Characterisation of these events using the SPI highlights major droughts that warrant further investigation, particularly the impacts of these droughts on water resources. This is especially key for drought events that are not commonly included in water resource management and drought planning, as pre-1920 droughts are rarely analysed in an operational water resources management context. The inclusion of pre-1920s droughts in the calculation of deployable output for a single WRZ shows insignificant changes in yield, supporting the findings of Spraggs et al. (2015). Whilst these historic droughts offer a chance to test the robustness of a WRZ to a greater range of drought characteristics, they do not appear to impact more severely than droughts experienced post-1920. Throughout the rest of this thesis further analysis of drought (meteorological and hydro(geo)logical) is focused on more recent events (e.g from 1962 onwards), which allows for greater spatial coverage of rainfall data across the STR and the inclusion of coeval surface water and groundwater data sets.

Whilst each meteorological drought has a unique set of characteristics, the examination of numerous drought events across the STR reveals common traits observed in a number events. This includes the identification of two drought typologies; (1) very long duration, moderate severity droughts (e.g. 1892-97) and (2) moderate duration, severe droughts (e.g 1921-23). Also identified is intra-regional variation; characterising drought events at numerous sites at a regional scale provides an insight in to the variability of droughts at a scale that is assumed to have event coherence. Both the 1995-97 and 2010-12 droughts provide examples of strong intra-regional variability in duration and severity. The 1995-97 drought is more severe in the east of the STR, whilst analysis of the 2010-12 drought reveals variation in drought onset from west to east. Improved understanding of intra-regional variability is particularly useful for water resources management and understanding drought risk.

Meteorological droughts in the STR exhibit phases of spatial and temporal coherence but also phases of drought variability. Correlation analysis of the SPI values at multiple sites across the STR suggest droughts are coherent across the STR, however, intra-regional variability in drought characteristics is observed. Sub-regionalisation of rainfall data identifies three clusters that reflect the west-east rainfall gradient across the STR. However, PCA of SPI results at 1-, 3-, 6-, 9- and 12-month accumulation periods identify two differing sub-regional clustering patterns that are dependent on the length of rainfall accumulation periods. Three sub-regional clusters for SPI-1 and SPI-3 are consistent with rainfall sub-regionalisation, and two sub-regional clusters at SPI accumulation periods greater than 6-months. This clustering suggests that meteorological drought is coherent across much of the STR (all sites within drought Cluster 2) with the exception of the far-west (Cluster 1). However, SPI-12 values calculated for the two sub-regional drought clusters show both periods of drought coherence and variability in the five droughts examined since 1962. Within each cluster inter-site variability in drought behaviour is also seen, suggesting that the PCA approach used in this analysis is not a sufficient measure of sub-regional drought variability at this scale.

Analysis of five droughts over 15 rainfall series suggests that the most severe droughts (minimum SPI values and number of months in extreme drought) exhibit less variability in the timing of event onset. Onset of the 1975-77 and 1995-97 droughts occur over 4- and 7-months respectively, whilst the 1990-92 and 2010-12 drought onset times occur over 17- and 14-months. However, this variability in pattern is not exhibited in drought termination, termination of the 1975-77 drought occurs over 10-months across the STR, whilst the termination of the 1990-92 event occurs over 11-months across the STR. The shortest termination range is 5-months for the 2010-12 drought. Based on the drought cluster heatmaps, the 1990-92 and 2010-12 droughts appear to have the most variability in drought behaviour between Clusters 1 and 2. Both the 1975-77 and 1995-97 droughts have greater coherence between drought clusters.

Whilst this chapter provides an insight into meteorological drought characteristics and their coherence across the STR, a more complete understanding of drought and its impacts on water resources is required. Therefore, it is necessary to examine drought in the terrestrial component of the water cycle, through the analysis of surface and groundwater datasets. The use of these datasets in combination with climatological data enables a greater understanding of the hydroclimatology of drought in the STR.

Chapter 5

Hydroclimatology of Drought

This chapter presents an examination of the hydroclimatology of drought in the STR utilising standardised drought indicators to investigate drought propagation and an investigation of the links between large-scale climate drivers and meteorological drought.

Chapter 5 presents the work undertaken to address objectives 3 to 5 of this thesis: *(3) examine the propagation of meteorological drought into the terrestrial component of the hydrological cycle and water resource system using a drought index approach to examine hydro(geo)logical drought responses using streamflow, reservoir and groundwater data, (3) explore drought structure at the catchment scale by coupling meteorological and hydro(geo)logical datasets to better understand the relationship between these drought types, and (5) to examine links between the atmospheric circulation indices; (1) Atlantic Multidecadal Oscillation, (2) North Atlantic Oscillation and (3) East Atlantic-West Russia and the SPI to better understand the potential of the SPI and these atmospheric circulation indices for drought monitoring.*

Where Chapter 4 has focused solely on meteorological drought, Chapter 5 also investigates hydrological and groundwater droughts and examines the relationship between meteorological and hydro(geo)logical droughts. This chapter is divided in to five sections, 5.1 presents a comparison between SPI values calculated using the standard parametric approach and a non-parametric approach, 5.2 uses standardised drought indicators to investigate drought propagation, 5.3 examines drought structures for individual drought events since 1942, 5.4 presents a synthesis of these drought structures and 5.5 investigates the relationship between drought indicators and the atmospheric drivers of drought.

5.1 Non-parametric Standardised Precipitation Index

The meteorological drought characterisations presented in Chapter 4 are computed using the standard SPI methodology based on the original approach outlined by McKee et al. (1993); this is a widely used and applied parametric approach which requires the fitting of a probability distribution to the data before normalisation. As outlined in Chapter 2, the question of which probability distribution is most suitable to compute the SPI is extensively explored (Guttmann, 1998; Sienz et al., 2011; Stagge et al., 2015b). The issue of identifying and using a suitable probability distribution also applies to the SPEI and other standardised drought indicators for hydro(geo)logical variables (e.g. SRI, SRI and SGI). Bloomfield and Marchant (2013) highlight this problem in relation to the large range of best fit distributions for groundwater level data across the UK, concluding that a parametric groundwater index does not allow objective comparisons between different groundwater level records, so a non-parametric methodology is required. In order to compute standardised drought indicators that are consistent and comparable across various meteorological and hydro(geo)logical variables in the STR, a non-parametric approach is employed here to permit the examination of different drought types. In order to assess whether non-parametric methodology can adequately characterise drought SPI results non-parametric SPI are compared with SPI values calculated using the original parametric computation employed by McKee et al. (1993). For clarity SPI values calculated using the non-parametric method are referred to as np-SPI results.

A comparison of the SPI and np-SPI for all 15 rainfall records across the STR from 1962-2012 at 1-, 3-, 6-, 9- and 12-month accumulation periods reveals consistent results between the two approaches; Figure 5.1 illustrates SPI and npSPI results for Rhayader. The consistency between the SPI and npSPI suggests that the non-parametric methodology outlined (section 3.3.2) can adequately characterise meteorological drought. The following sections examine meteorological and hydro(geo)logical droughts using the non-parametric approach.

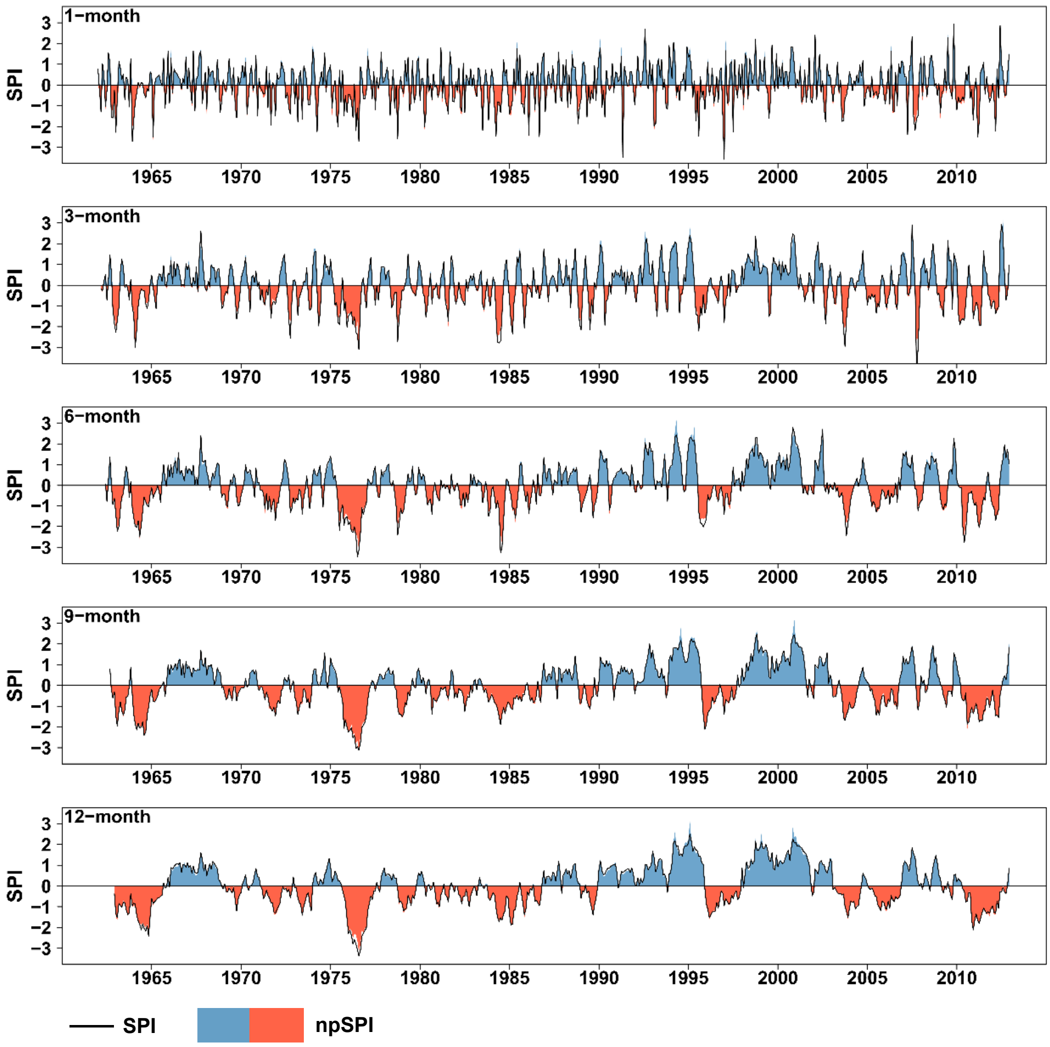

Figure 5.1: SPI and npSPI results for Rhayader at 1-, 3-, 6-, 9- and 12-month accumulation periods

5.2 Hydro(geo)logical Drought and Drought Propagation in the STR

To characterise hydrological and groundwater drought, standardised drought indicators are computed for streamflow, reservoir storage and groundwater levels at a number of locations across the STR; these drought indices are referred to as the SSI, SRI and SGI respectively. As outlined in Chapter 3 each index is computed using monthly data, and unlike the SPI without the use of multiple accumulation periods due to the highly auto-correlated nature of these hydro(geo)logical datasets. To examine drought propagation and the relationship between meteorological and hydro(geo)logical droughts the SSI, SRI and SGI are correlated with SPI values computed across multiple accumulation periods, the accumulation period that has the strongest correlation with SSI, SRI and SGI values are considered to be the most representative hydro(geo)logical drought response (propagation) to meteorological drought; termed SPI*max*. SPI values are computed using the 15 rainfall datasets outlined in Chapter 3, rainfall datasets selected for analysis with SSI, SRI and SGI values are based on their proximity to the hydro(geo)logical datasets. In this section, all analyses are computed for a 37-year period from 1975-2012, which enables the use of all available hydrological and hydrogeological data sets collated in this thesis.

Hydrological drought is characterised across the STR using monthly streamflow and reservoir storage data to compute the SSI and SRI. As outlined in Chapter 3, streamflow data is included from 15 gauging stations across the Severn, Trent and Wye catchments, the catchment areas of the 15 gauging stations range in size from 83 km^2 to 4325 km^2 and cover a wide range of land use and geologies. Reservoir storage data is provided by two reservoir groups, the Elan Valley Group (west STR) and Derwent Valley Group (north STR). As described in Chapter 3, these reservoir groups are both formed of multiple reservoirs in the headwaters of the Wye (Elan Valley Group) and Derwent (Derwent Valley Group) catchments respectively. Although six reservoir storage records across the STR are digitised for analysis in this thesis, the analysis in this section uses just the Elan Valley and Derwent Valley groups as a result of completeness of these records, length of available data and their strategic importance for Severn Trent Water. Groundwater drought is characterised using groundwater level data from nine observation boreholes including the four main aquifer types used by Severn Trent Water for public water supply abstraction.

5.2.1 Standardised Streamflow Index (SSI)

The SSI identifies multiple drought events between 1975 and 2012 based on the 15 streamflow records used to characterise hydrological droughts across the STR (Figure 5.2, 5.3). These droughts are consistent with meteorological droughts identified in Chapter 4 and include notable events in 1975-77, 1990-92, 1995-97 and 2010-12. Figure 5.3 highlights the most notable drought phases e.g. 1995-97, but there is also a number of single months with SSI values <-1. At short accumulation periods (< 6-months) the SPI exhibits more short-term variation or noise, as the presence of this noise is identified in the SSI values, suggesting that streamflow responds quickly to meteorological conditions. To investigate the response of the hydrological system to meteorological conditions SSI values are correlated with SPI values at accumulations periods from 1- to 6-months to identify SPI*max*, which is the SPI accumulation period that has strongest correlation with the SSI.

Results of the analysis between SSI and SPI values are presented in Table 5.1 and Figure 5.2. Across the STR all streamflow record hydrological drought response to meteorological drought (SPI*max*) is 5-months or less. SPI*max* values range from 1-month (site 55026 on the headwaters of the River Wye) to 5-months (sites 54012 on the River Tern and 54016 River Roden). The most common SPI*max* value is 2-months accounting for the strongest SSI-SPI correlation at 8 of the 15 sites; this is followed by a SPI*max* value of 3-months at four sites. Based on this analysis streamflows in the STR show sensitivity to short-term (< 6-months) meteorological variability.

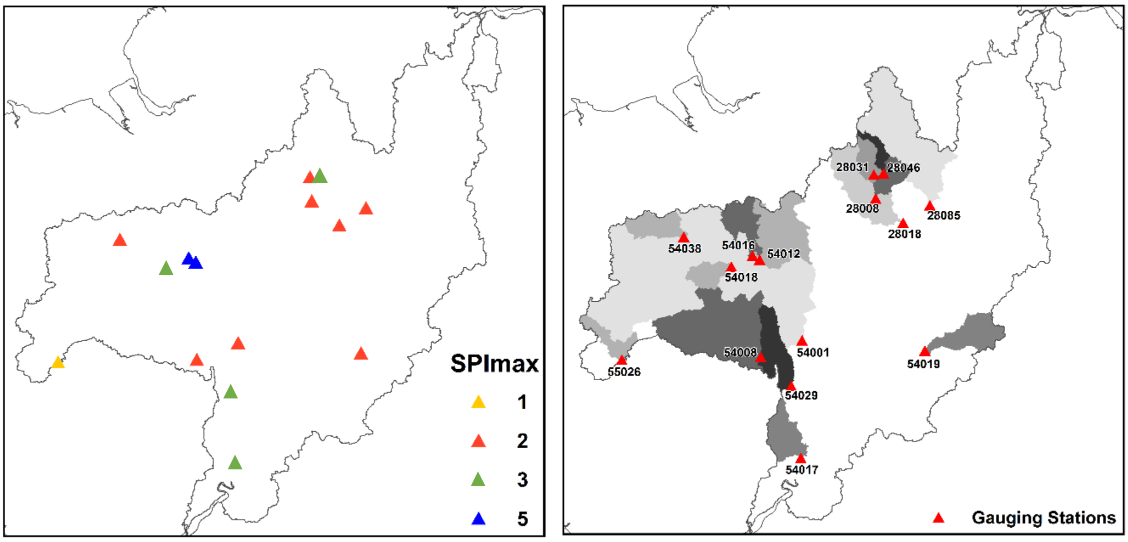

Figure 5.2: (a) SPI*max* values in months for 15 streamflow records across the STR, (b) gauging station site numbers with associated catchment areas shaded in grey tones

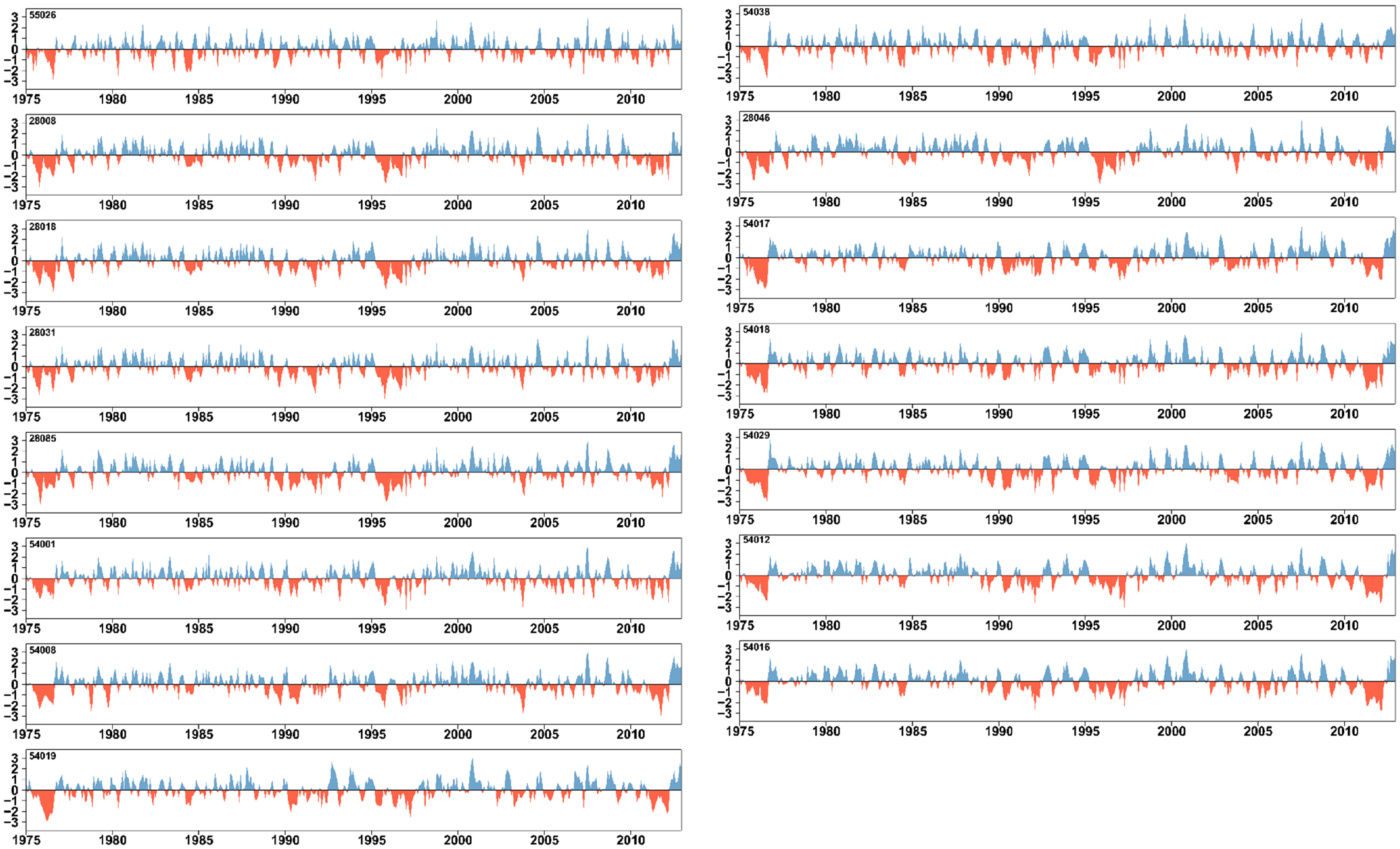

Figure 5.3: SSI and SPI values at SPI*max* for all streamflow gauges

Table 5.1: SPI*max* and associated correlation coefficients for SSI values and catchment and climate characteristics *SAAR= standard annual areal rainfall (1971-2000)

Site	SPI*max* (months)	SPI*max*-SSI Correlation	Catchment Area (km^2)	BFIHOST	BFI	SAAR* (mm)
55026	1	0.78	174	0.42	0.37	1618
28008	2	0.77	399	0.56	0.62	1020
28018	2	0.77	883	0.53	0.61	935
28031	2	0.78	148	0.46	0.52	1096
28085	2	0.78	1054	0.55	0.62	1012
54001	2	0.74	4325	0.54	0.53	913
54008	2	0.78	1134	0.61	0.55	878
54019	2	0.70	347	0.42	0.48	654
54038	2	0.76	229	0.48	0.47	1292
28046	3	0.75	83	0.65	0.79	1141
54017	3	0.71	293	0.57	0.47	685
54018	3	0.73	178	0.51	0.50	765
54029	3	0.74	1480	0.60	0.55	818
54012	5	0.70	852	0.62	0.69	694
54016	5	0.69	259	0.62	0.61	693

The correlation coefficients between the SSI and SPI*max* values range from 0.69 (site 54016) to 0.78 (sites 55026, 28031, 28085 and 54008) and are all statistically significant at the 0.05 significance level, indicating a strong relationship between meteorological and hydrological drought. The lowest SSI-SPI correlation coefficients at 0.69 and 0.70 (sites 54016, 54012 and 54019) are associated with streamflows moderately influenced by abstractions, effluent returns and flow augmentation by groundwater pumping (based on the National River Flow Archives' Hydrometric Register descriptions). However, the highest correlation coefficients at 0.78 are observed at four sites that include streamflows that are natural within 10% of Q95 flows (site 28031) and those that are substantially modified by reservoirs, abstractions and effluent returns (site 28085 on the River Derwent).

Analysis of drought characteristics, particularly drought frequency, duration and severity identifies variability across the STR. For each streamflow dataset drought frequency measured is by calculating the number of times the SSI reaches a value equal to or less than -1 (that is independent of a previous drought event) including even single months with an SSI <-1. Results of this analysis identify that drought frequency ranges from 39 to 21 drought events over the 37 years. Sites that have the fastest response time (smaller SPI*max*) to meteorological droughts tend to exhibit more frequent, shorter duration drought events (Figure 5.4). There is a strong inverse relationship (correlation coefficient = -0.65) between SPI*max* and drought frequency, as SPI*max* increases drought frequency decreases (Figure 5.4). Site 55026 in the headwaters of the River Wye exhibits the shortest SPI*max* accumulation period at 1-month and has the highest frequency of drought occurrence at 39 across the STR. Sites 54012 and 54016 have the largest SPI*max* values and lowest drought occurrence frequencies at 22 and 21 events respectively. However, this link is not straight forward, for example, site 28018 has a SPI*max* of 2-months, but a drought frequency of 23.

Drought duration is computed by summing the months between drought onset (SSI =<-1.00) and termination (SSI >= 0). Both average drought duration and maximum drought duration show a strong positive relationship with SPI*max* (Figure 5.4); correlation coefficients are 0.76 and 0.75 respectively (Table 5.2). Minimum drought duration does not show the same the strength of relationship with a correlation coefficient of 0.41. Average drought durations range from 5-months for site 55026 (SPI*max* = 1-month) to 12-months for sites 54012 and 54016 (SPI*max* = 5-months). Whilst the two SSI series with the largest SPI*max* values have the longest maximum drought durations, the SSI series with the smallest SPI*max* does not have the shortest maximum duration. Minimum drought durations range from 2- to 5-months with very little clear trend, minimum drought durations for site 55026 (SPI*max* = 1-month) and 54012 (SPI*max* = 5-months) both have a minimum drought duration of 3-months.

Drought severity characteristics for each SSI series is calculated by summing the negative SSI values for the duration of each drought. It is important to note that this severity total summing procedure used to investigate variability in drought response between the SDI series and does not have any physical realism to compare drought events. Results for the relationship between average drought severity and the SPI*max* are the strongest for all drought severity characteristics (-0.69) (Table 5.2); average event severity decreases as the

SPI*max* decreases. Whilst most sites follow this trend there are some exceptions and the range of average drought severity for the sites with a 2-month SPI*max* varies from -14.00 to -7.00. This large range of values for drought severity characteristics is mirrored in both the minimum and maximum severity analyses. These findings can be summarised as higher (lower) SPI*max* values are associated with less (more) frequent, longer (shorter) duration, more (less) severe droughts. However, whilst there is a general trend for greater maximum drought severity totals for SSI series with larger SPI*max* values, sites with a 2-month SPI*max* have maximum drought severity totals that range from -29.00 to -12.00.

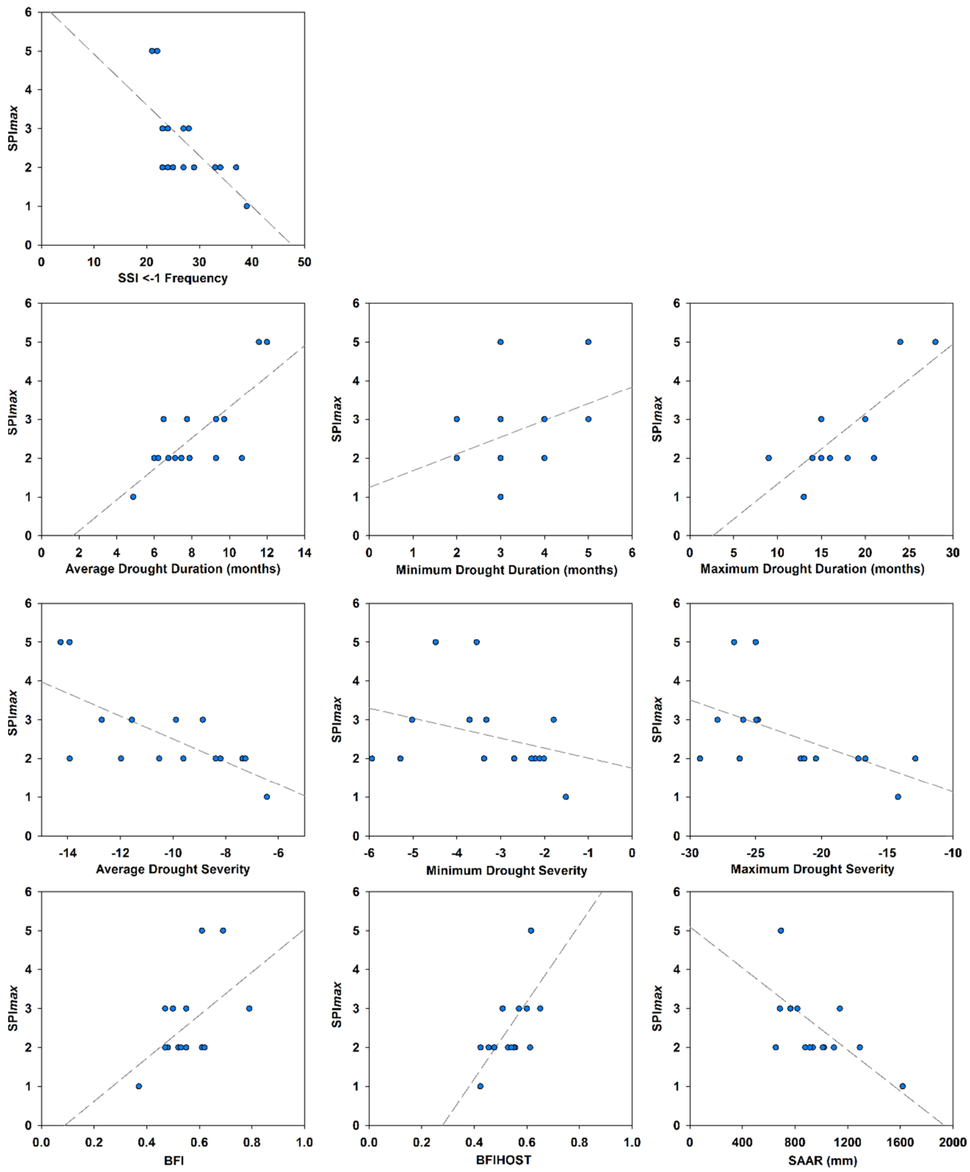

Figure 5.4: Relationship between SPI*max* and hydrological drought characteristics and SPI*max* and catchment/climate properties

The role of catchment storage and climate characteristics in drought propagation are investigated using base-flow and standard annual areal rainfall (SAAR) data; these are correlated with SPI*max* values identified for each streamflow record. Two catchment storage indicators are used- (1) base-flow index (BFI), and (2) BFIHOST. BFI is the ratio of streamflow that is attributed to base-flow from the streamflow total, whilst BFIHOST is a measure of catchment responsiveness derived from the hydrology of soil type classifications (HOST) formulated by the Institute of Hydrology (Boorman et al., 1995). The BFI values are derived through the separation of the hydrograph technique based on the methodology outlined by Gustard et al. (1992). SAAR values are the mean of annual rainfall totals for each catchment for the standard period 1971-2000. Both BFIHOST and SAAR values are obtained through the catchment descriptors of the National River Flow Archive (http://nrfa.ceh.ac.uk/data/search). For both BFI and BFIHOST, the larger the value the greater the contribution of streamflow is from the subsurface.

Results of this analysis indicate a positive relationship between SPI*max* and both catchment storage descriptors, with Pearson correlation coefficients of 0.64 (BFIHOST) and 0.50 (BFI), both significant at the 0.05 level (Figure 5.4). Catchments with higher BFI or BFIHOST values show a tendency towards larger SPI*max* values that indicate a slower hydrological drought response. However, this relationship is not straightforward, catchment 28046 has the highest BFI/BFIHOST values (BFIHOST = 0.65, BFI = 0.79) but a 3-month SPI*max.* Other catchments with 3-month SPI*max* values have lower catchment storage values. Results of the analysis between SPI*max* and SAAR show an inverse relationship (Pearson's correlation coefficient = -0.62) with lower SAAR values attributed to higher SPI*max* values. However, SAAR totals for the catchments with 2-month SPI*max* values range from 654 to 1292 mm.

To further examine the links between hydrological drought characteristics and catchment/climate controls, BFIHOST and SAAR values are correlated with average, minimum and maximum drought duration and severity values (Figure 5.6). Average and maximum drought duration characteristics and BFIHOST are strongly positively correlated, correlation coefficients are 0.61 and 0.60 respectively. The relationship between maximum and average drought severity totals and BFIHOST are negatively correlated (-0.58 and -0.65), more negative severity totals are associated with larger BFIHOST values. The links between SAAR and drought duration/severity characteristics are generally weaker than those for BFIHOST (Table 5.2). The link between SAAR and drought duration is a negative moderate relationship, -0.56 and -0.41 for average and maximum durations respectively. Correlations between SAAR and drought severity show a moderate positive relationship with correlation coefficients for average severity 0.55 and maximum severity 0.56.

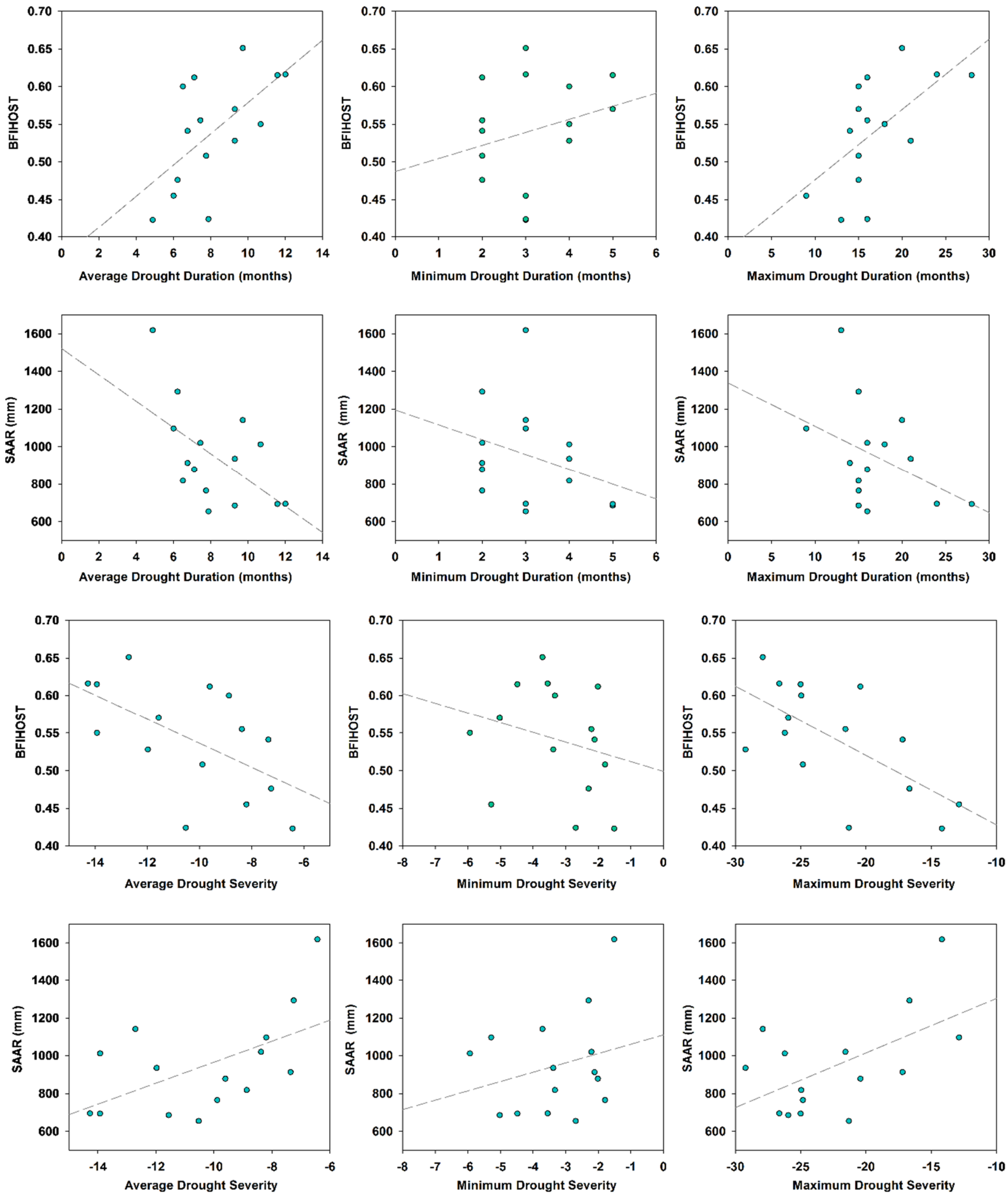

Figure 5.5: Relationships between drought severity and duration characteristics with BFIHOST and SAAR

Table 5.2: Pearson's correlation coefficients for relationships between drought characteristics and SPI*max*, BFIHOST and SAAR. All significant at α =0.05.

	Drought Frequency	Average Duration	Min Duration	Max Duration	Average Severity	Min Severity	Max Severity
SPI*max*	-0.65	0.76	0.41	0.75	-0.69	-0.32	-0.54
BFIHOST	-0.75	0.61	0.25	0.60	-0.58	-0.25	-0.65
SAAR	0.67	-0.56	-0.32	-0.41	0.55	0.26	0.56

An example of the influence that catchment storage can have on hydrological drought characteristics is exemplified by the contrasting characteristics for SSI series 28031 and 28046. These streamflow gauges are located in adjacent catchments within the wider River Dove catchment but have notably different BFIHOST values and catchment characteristics; the catchment for streamflow gauge 28046 has a 0.65 BFIHOST compared to 0.45 for 28031. Drought frequency varies between the sites from 33 to 24 times in 37-years for 28031 and 28046 respectively. Maximum drought duration and severity are particularly variable from 9- to 20-months and severity totals between -12.9 and -27.9 for 28031 and 28046 respectively.

5.2.2 Standardised Reservoir Index (SRI)

The SRI series are computed for the Derwent Valley and Elan Valley reservoir groups; both identify a number of droughts between 1975 and 2012 including the 1975-76, 1990-92 and 1995-96 events. The SRI series are correlated with the SPI for accumulation period from 1- to 6-months to identify SPI*max*. In both cases SPI*max* is 5-months (Table 5.4). SRI-SPI*max* correlation coefficients range between 0.55 and 0.57, both significant at the 0.05 level. These are the lowest correlation coefficient values obtained across the SPI*max* calculations for the SSI, SRI and SGI series. Analysis of drought frequency and duration characteristics for reservoir groups reveals a degree of similarity in drought behaviour (Table 5.3). Drought frequency (the number of times the SRI reaches <-1) is 17 and 20 over 37-years at Derwent Valley and Elan Valley respectively. Average drought duration is 7-months at Derwent Valley and 9-months at Elan Valley with minimum drought durations between 3- and 4-months and maximum durations between 17- and 19-months for Derwent Valley and Elan respectively.

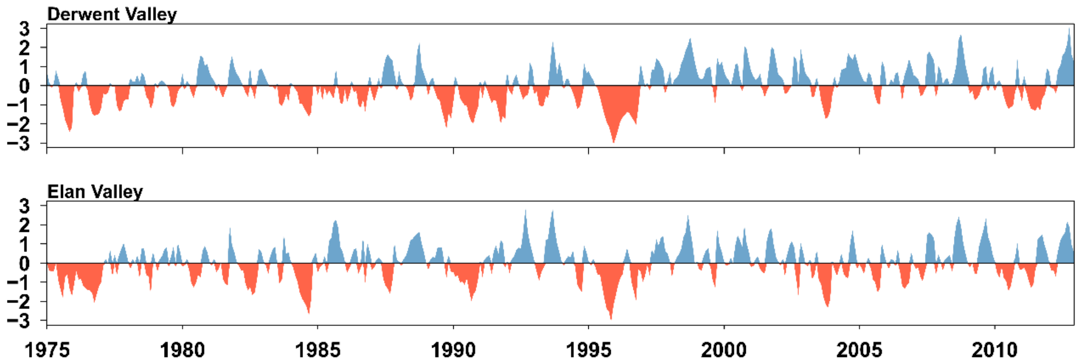

Figure 5.6: SRI series for the Derwent Valley and Elan Valley reservoir groups

Table 5.4: Drought Characteristics for the SRI

Reservoir	SRI <-1	Average Duration (months)	Min Duration (months)	Max Duration (months)	Average Severity	Min Severity	Max Severity
Derwent Valley Group	17	7	4	17	-10.9	-3.7	-31.8
Elan Valley Group	20	9	3	19	-10.8	-2.7	-23.7

Table 5.3: SPI*max* and associated SRI-SPI*max* Pearson's correlation coefficients

Reservoir	SPI*max*	Max SPI-SRI Pearson Correlation
Derwent Valley Group	5-months	0.57
Elan Valley Group	5-months	0.55

Both the Derwent Valley and Elan Valley reservoir groups are situated in the headwaters of rivers that are included in the SSI analysis, the River Derwent and the River Wye. Analysis of both streamflow and reservoir levels within the same catchments highlights the 'smoothing' effect reservoirs have on the natural hydrological cycle. Site 55026 on the River Wye has a 1-month SPI*max* whilst the Elan Valley reservoir group has a 5-month SPI*max*. Site 28085 on the River Derwent, downstream of the Derwent Valley reservoirs, has a 2-month SPI*max* whilst the Derwent Valley reservoirs SPI*max* is 5-months.

5.2.3 Standardised Groundwater Index (SGI)

The SGI is computed for nine groundwater observation boreholes in the four main aquifer types across the STR (Figure 5.6). All SGI values identify a number of droughts in the analysis period including the 1975-76, 1990-92, 1995-96 and 2010-12 events, which are also identified in the meteorological and hydrological drought characterisations. However, there is notable variation in variability of the SGI series between groundwater level records; the sites Hucklow South, Ampney Crucis and Alstonfield exhibit considerably more variability than Ram Hall, Nuttalls Farm and Heathlanes (Figure 5.5). A characterisation of groundwater drought using the SGI (Table 5.5) reveals further insight into the variation of groundwater drought behaviour across the STR. The frequency of the SGI reaching <-1 over the 37-year analysis ranges from 27 at Alstonefield to five times at Four Crosses, Ram Hall, Nuttalls Farm and Heathlanes. Average drought duration varies from 6-months (Hucklow South) to 31-months (Nuttalls Farm and Heathlanes) with maximum event durations 9-months (Hucklow South) to 53-months (Nuttalls Farm). Average drought severity ranges from -7.3 (Hucklow South) to -42.2 (Nuttalls Farm) and maximum drought severity ranges from -14.7 (Hucklow South) to -50.4 (Four Crosses).

To identify SPI*max* cross-correlation analysis is performed between the SGI and the SPI for accumulation periods from 1- to 40-months for lags up to 10-months for each groundwater level record. SPI*max* values for each SGI series range from 4-months (Hucklow South) up to 40-months (Heathlanes) (Table 5.3, Figure 5.8); groundwater drought response to meteorological drought is highly variable across the STR. Correlation coefficients for each of the SPI*max* values ranges from 0.58 (Ampney Crucis) to 0.86 (Nuttalls Farm). Figure 5.8 presents the SGI-SPI cross-correlation results, at five of the nine groundwater records SPI*max* values are associated with cross-correlation lags from 1- to 2-months, the remaining four sites have a lag of zero.

The variation in SPI*max* values across the STR highlights the role of geological controls on the propagation of drought. The fastest responding SGI series (Hucklow South, Ampney Crucis and Alstonefield) are all situated on Carboniferous Limestone or Jurassic limestone aquifers with SPI*max* values between 4- and 6-months, whilst the slowest responding series all sit on Permo-Triassic sandstone aquifers. Across the four groundwater records situated on limestone SPI*max* values range from 4-months (Hucklow South) to 12-months (Hod Hill

Farm), and there is a large range of SPI*max* values within the Permo-Triassic sandstone aquifers from 11-months (Anthony's Cross) to 40-months (Heathlanes).

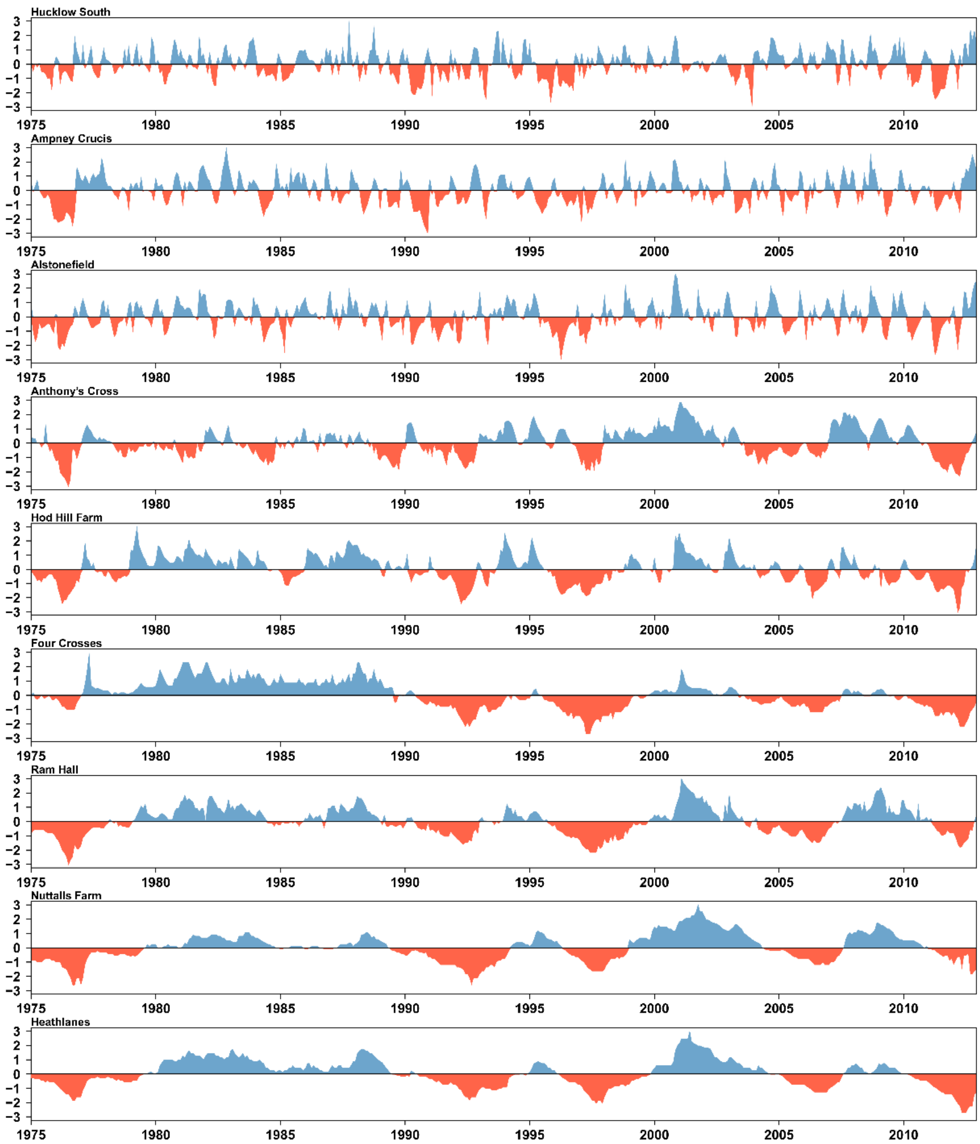

Figure 5.7: SGI series for groundwater levels in nine observational boreholes in the STR

The large range in SPI*max* values across the aquifers in the STR results in highly variable drought characteristics. The fastest responding groundwater levels exhibit more frequent, shorter duration droughts than sites that have a slower response to meteorological conditions. The relationships between SPI*max* values and drought frequency, duration and severity characteristics are shown in Figure 5.8. There is a strong negative relationship between SPI*max* values and the frequency that SGI values reach <-1 (Pearson's correlation =-0.81). The four slowest responding groundwater levels experience drought conditions five times over the 37-year analysis period, whilst the three fastest responding sites experience between 25 and 27 events in the same period (Figure 5.9). There is a very strong positive relationship between SP*Imax* and drought duration, the larger the SPI*max* value the longer drought duration for both average and maximum durations, with Pearson's correlations at 0.98 and 0.95 respectively. Correlation coefficients between SPI*max* and minimum and average drought severity are also very strong at -0.91 and -0.90 respectively. SGI series with larger SPI*max* values have larger drought severity totals. However, the relationship between maximum drought severity and SPI*max* is slightly weaker (-0.78).

Table 5.5: Groundwater Drought Characteristics for nine observation boreholes in the STR.

Borehole	**Drought Frequency**	**Average Duration (months)**	**Min Duration (months)**	**Max Duration (months)**	**Average Severity**	**Min Severity**	**Max Severity**
Hucklow South	25	6	2	9	-7.3	-1.6	-14.6
Ampney Crucis	25	8	3	13	-8.9	-4.0	-23.2
Anthony's Cross	27	7	2	12	-10.0	-3.5	-15.3
Hod Hill Farm	10	15	12	19	-20.8	-16.9	-28.2
Four Crosses	7	16	5	32	-23.7	-17.3	-35.0
Ram Hall	5	28	21	35	-34.9	-19.4	-50.4
Nuttalls Farm	5	28	17	40	-42.4	-33.4	-47.8
Heathlanes	5	37	22	53	-39.7	-24.6	-47.6

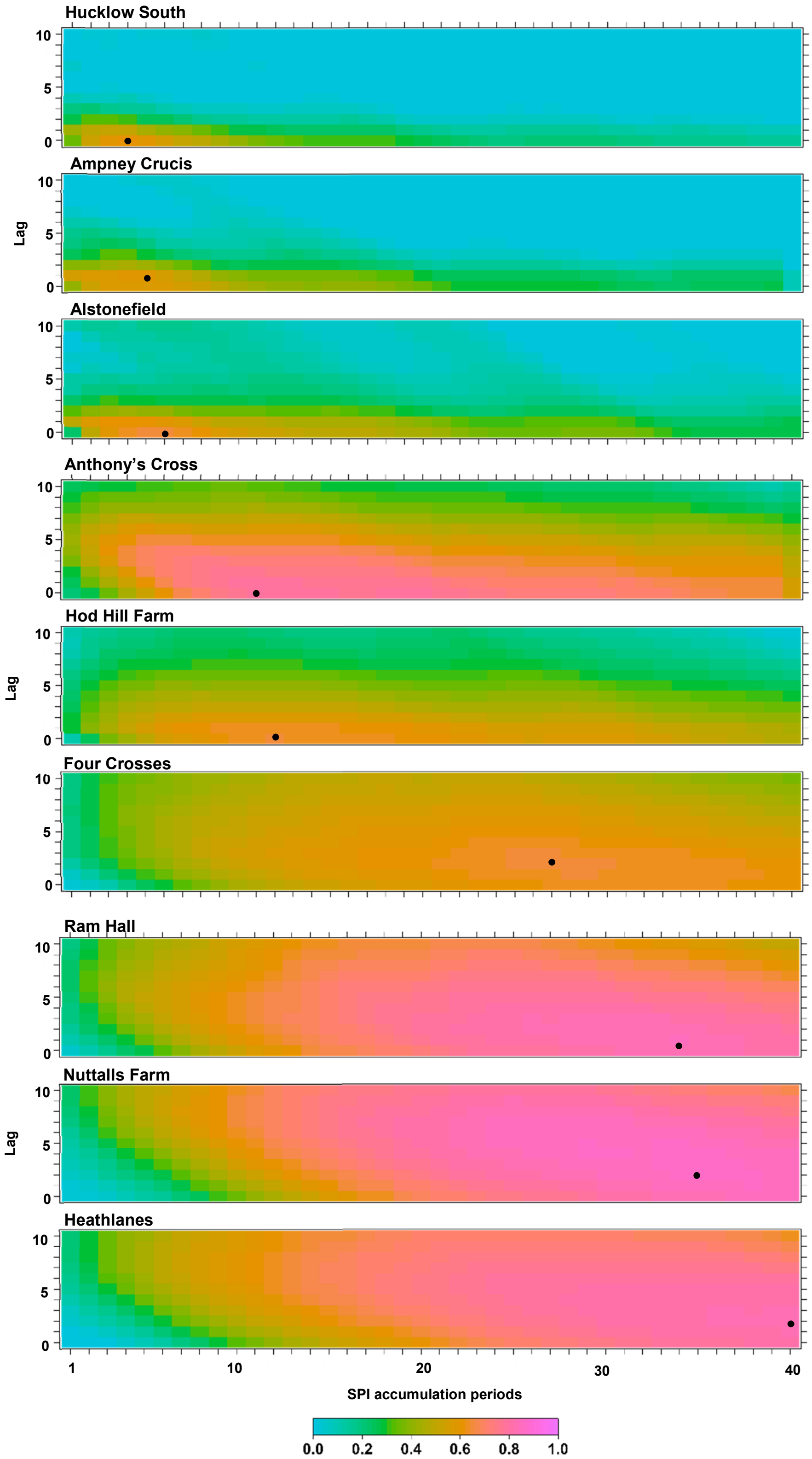

Figure 5.8: Heatmaps for SGI-SPI cross-correlation results with highest correlation marked with a black circle.

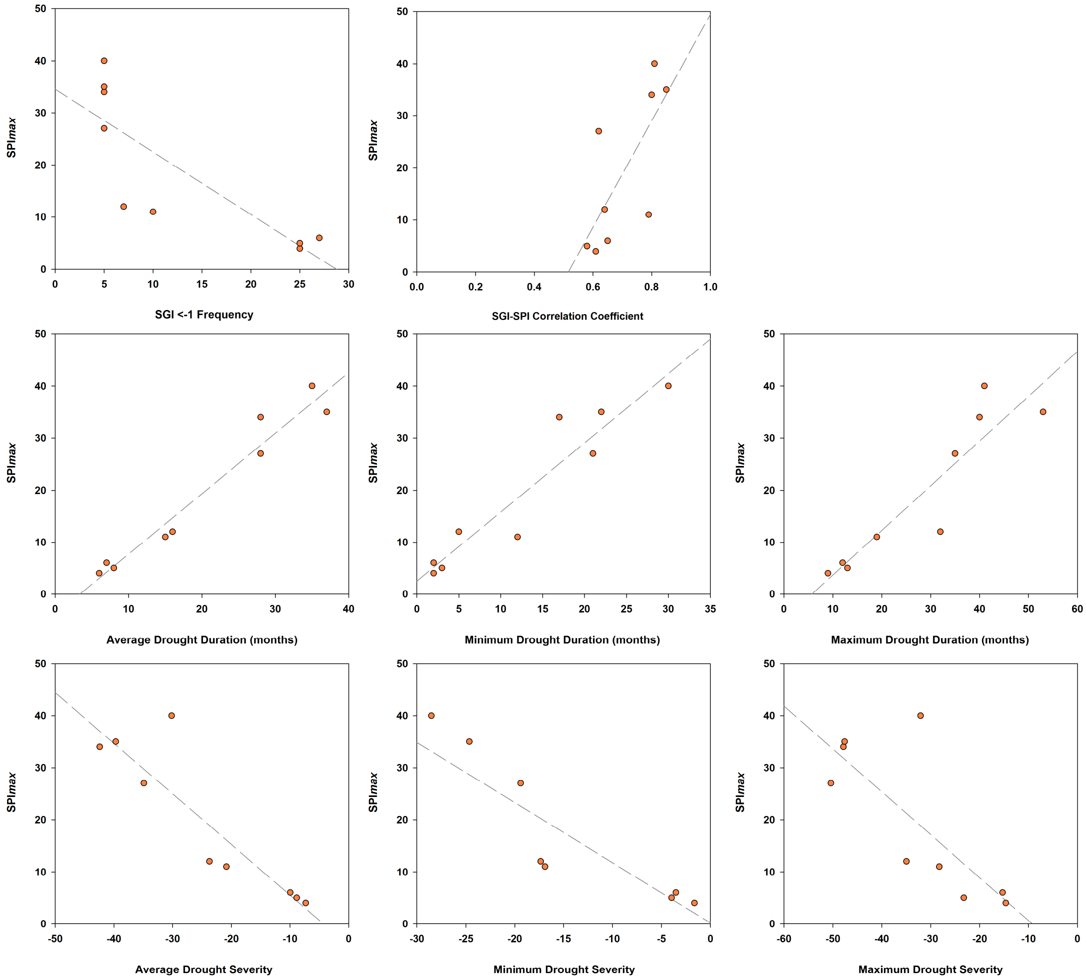

Figure 5.9: The relationship between SPI*max* values and drought frequency, SPI-SPI correlation coefficients at SPI*max*, drought duration and severity characteristics.

5.3 Catchment Scale Examination of Drought Structure

In order to develop a better understanding of the relationship between meteorological, hydrological and groundwater droughts and the interactions between these drought types section 5.3 presents the examination of individual drought events at a catchment scale (Figure 5.10). This section focuses on drought structure, including the characteristics of drought onset and termination (Figure 5.11). The gradients are computed between d*ons* (last positive value before SDI < 0) and d*min* (minimum SDI value in a drought event) and d*min* and d*term* (first positive value after SDI > 0) to identify the rate of drought onset and termination. Drought severity is considered in two ways; (1) the minimum SDI value during each drought (d*min*) and (2) the total sum of the negative SDI values for the duration of each event. Where drought events are formed of multiple phases, drought duration and severity are summed over all the events so the characteristics can be consistently compared between all SDI series. Drought duration is summed by the number of months between drought onset at SDI ≤-1 and termination at SDI ≥0. A drought phase is considered to be a component of drought event in which there are is a brief termination (e.g. 2-months) before the onset of a subsequent drought phase; a number of drought phases are the constituent parts of a drought event. These characteristics are computed for each of the SDI series to identify the interactions between meteorological, hydrological and groundwater droughts and to establish any common drought structure features identified between individual events. Six catchments across the STR are used in this analysis (Figure 5.10); each catchment includes SPI-3 and SPI-6 series for one rainfall record and at least one SSI series, four catchments include SGI data and two include SRI data. Four drought events are examined- 1975-76, 1990-92, 1995-96 and 2010-2012. Full tabulated results for the catchment scale analysis are found in Appendix C.

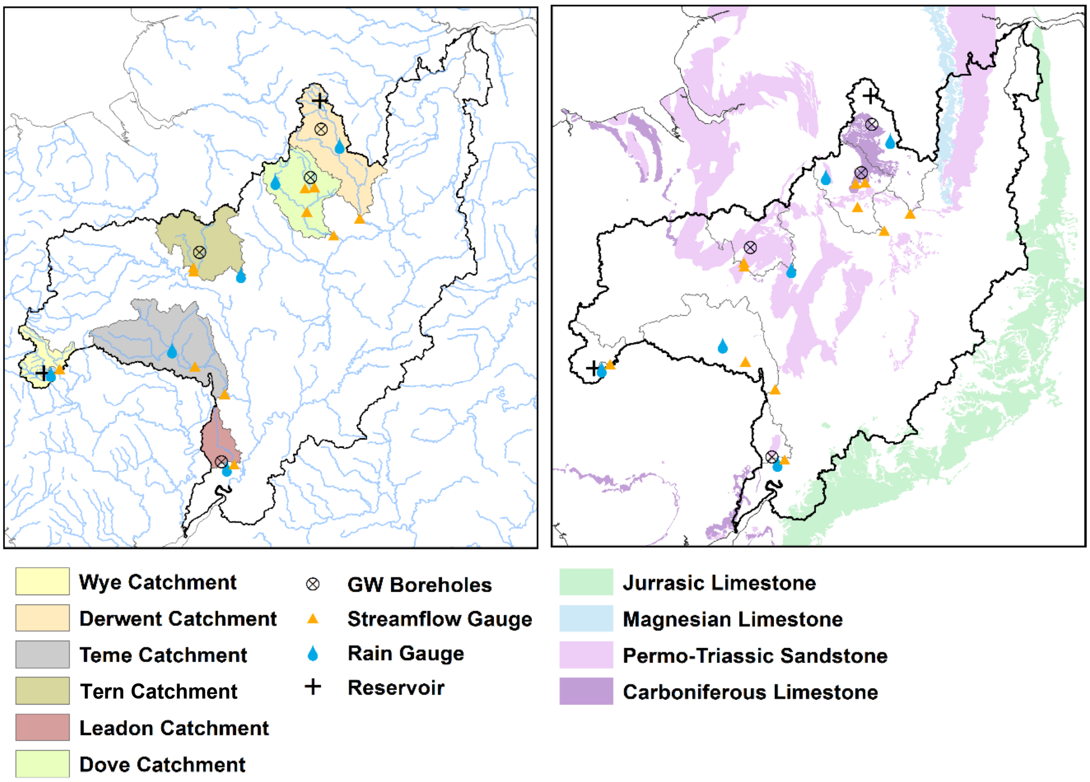

Figure 5.10: Catchments used in catchment scale drought structure analysis (a) catchment areas and rivers, (b) primary aquifer types in the STR

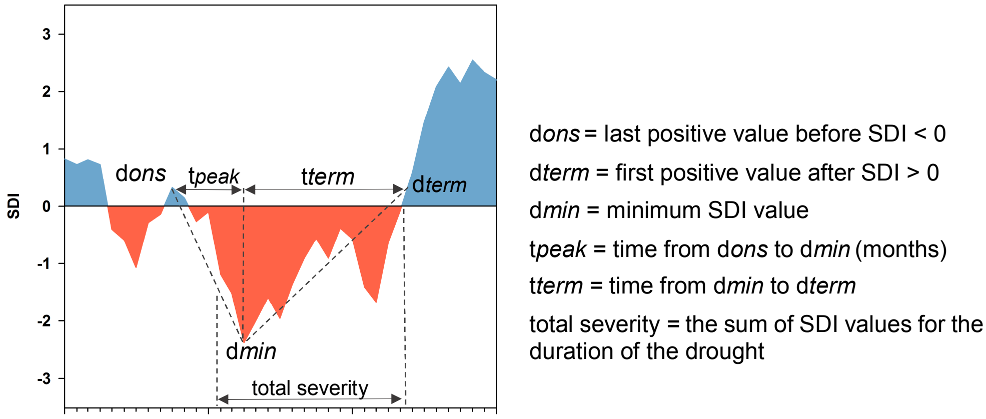

Figure 5.11: Drought characterisation

5.3.1 Derwent Catchment

Drought structure analysis for the Derwent catchment includes the SPI, SSI, SGI and SRI; this is the only catchment containing all of the SDI types (Figure 5.10). SPI values are computed using the Chatsworth rainfall record, SSI values using streamflow data for site 28085; the SGI is computed for Hucklow South and SRI values are from the Derwent Valley reservoir group. SPI*max* results for the SSI, SRI and SGI values are 3-months for the SSI, 4-months for the SGI and 5-months for the SRI. The four drought events examined are presented in Figure 5.11.

1975-76

The onset characteristics of the 1975-76 drought (Figure 5.12a) are distinct between the SPI and the SSI, SGI and SRI series. The SSI and SRI have similar d*ons* to d*min* characteristics: SSI and SRI gradients are -0.51 and -0.53 over 6- and 7-months (t*peak*) whilst the SGI has a shallower gradient (-0.25) with a 7-month t*peak*; each of these SDI series reach d*min* in November 1975. Both the SPI-3 and SPI-6 have shallower d*ons* to d*min* gradients and t*peak* durations, SPI-3 has a -0.05 gradient over 2-months and the SPI-6 has -0.09 gradient over 19-months; reaching d*min* in August 1976.

Both the SGI and SRI series reach drought termination in January (SGI) and February (SRI) 1976, before a second onset phase occurs in February 1976 and September 1976 respectively. Whilst the SRI responds in a similar way to the SSI and SGI in its first drought phase, the second drought phase does not show the same consistency; drought termination occurs in October 1976 in all stores except the SRI where drought conditions continue into

1977 (terminating in May 1977), there is a 7-month lag in drought termination between the reservoirs and other SDI series in the catchment. Analysis of the total storage volume of the reservoirs reveals that winter recharge during 1976 did not fully replenish the reservoirs to maximum storage, which typically occurs by January each year.

Minimum SDI values (d*min*) range from -1.94 (SGI) to -3.06 (SPI-3 and SSI), the d*min* values for SPI-3 and SSI are the lowest 3-month rainfall totals and monthly streamflow totals in the analysis period. SDI severity totals over the duration of the drought for the SPI, SSI and SRI range from -18.16 (SRI) to -23.66 (SPI-6) with consistent severities for SPI-3 and SSI. The SGI total is notably less severe with a total of -10.61.

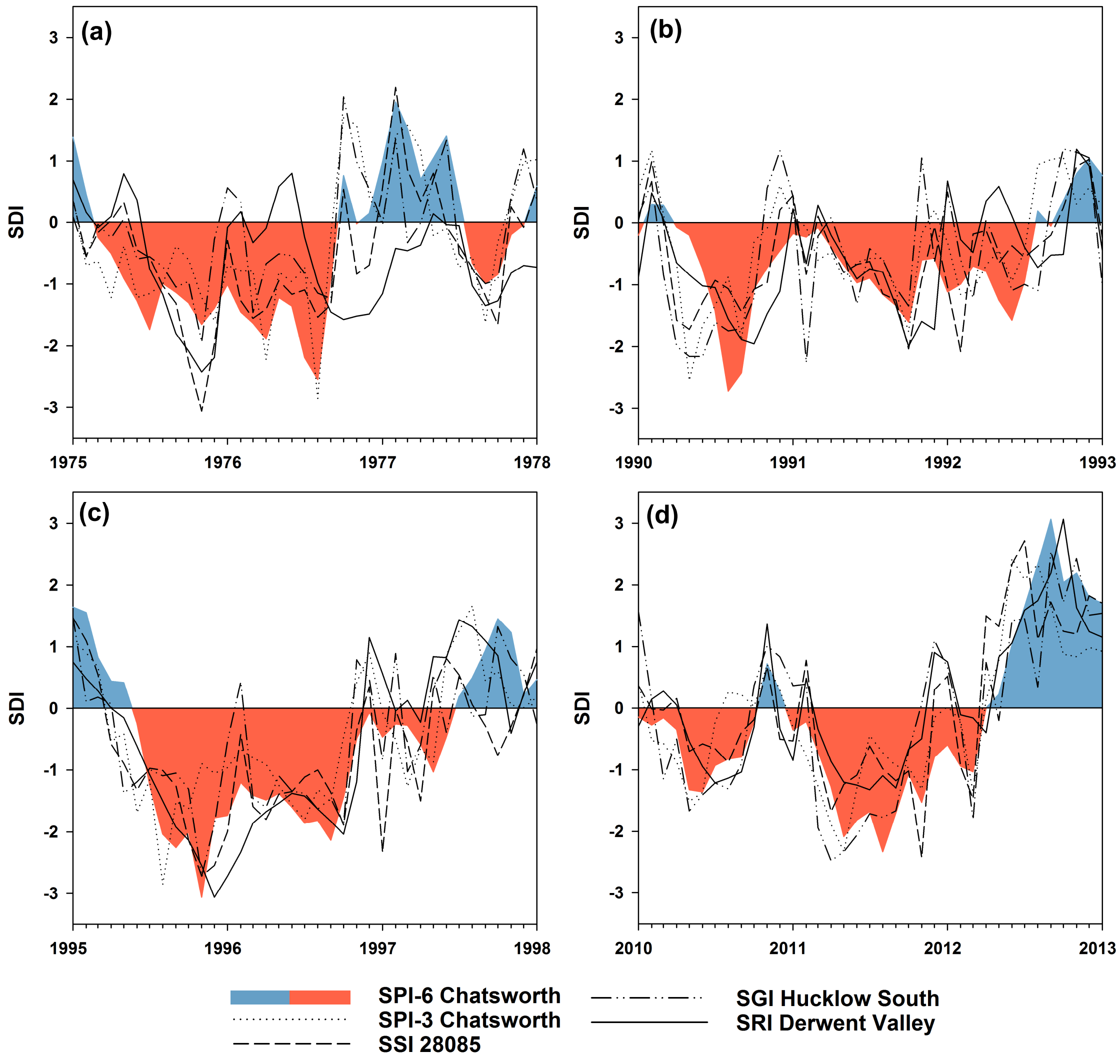

Figure 5.12: SDI plots for the Derwent catchment for individual drought events (a) 1975-76, (b) 1990-92, (c) 1995-96, (d) 2010-12

1990-92

Within the 1990-92 drought (Figure 5.12b), SPI-3, SSI, SGI and SRI have two drought phases whilst the SPI-6 series identifies a single event. In the first drought phase SPI-3, SGI and SSI all reach d*min* concurrently in May 1990; the SSI has a -0.96 d*ons* to d*min* gradient over 4-months which is the fastest drought onset to peak severity phase across the four events examined in the Derwent catchment. During this first drought phase the SRI peaks 4-months after the SPI-3, SSI and SGI. The SPI-3, SSI and SGI terminate during December 1990 and January 1991, in the second drought phase all series in the catchment excluding the SSI reach d*min* in October 1991. In both drought phases the SRI displays similar onset and termination characteristics, d*ons* to d*min* gradients are -0.26, with 8-month t*peak* durations and d*min* to d*term* gradients of 0.69 and 0.78 with 4-month t*term* durations. The SPI-3, SSI and SGI drought severity totals are consistent ranging from -20.17 to -21.00. Drought severity totals for the SPI-6 and SRI show greater variation at -24.78 (SPI-6) and -16.67 (SRI).

1995-96

Onset characteristics of the1995-96 drought (Figure 5.12c) are the most uniform across the four drought events examined in the Derwent catchment. For example, d*ons* to d*min* gradients range from -0.15 to -0.59 with t*peak* durations ranging from 6- to 9-months. Minimum SDI values (d*min*) for the SPI-6, SGI, SSI and SRI are all reached in November (SPI-6, SSI and SGI) and December 1995 (SRI); d*min* for SPI-3 occurs earlier in August 1995. November 1995 accounts for the lowest 6-month rainfall total (SPI-6, -3.06) and monthly reservoir storage volumes (SRI, -3.06) in the analysis period. Drought durations are consistent between SPI-3, SGI, and SSI and SRI ranging from 17- to 18-months, whilst the SPI-6 identifies a 24-month duration drought. Groundwater drought occurs in two phases with termination occurring in February 1996. The d*min* to d*term* gradient for both of the groundwater drought phases are steep (1.07 and 2.66) with 4- and 2-month t*peak* durations. Based on the all SDI severity totals this event is the most severe drought in the Derwent Catchment between 1975 and 2012. The SRI severity total is particularly notable at -31.82; all other SRI totals are between -11.28 (2010-12) to -18.16 (1975-76).

2010-12

The 2010-12 event (Figure 5.12d) is formed of two drought phases. These phases are April to September 2010 and March 2011 to March 2012. During the first drought phase the SSI does not reach drought conditions. The onset characteristics for the SPI-3, SGI and SRI series in the first drought phase are consistent with d*ons* to d*min* gradients between -0.41 and -0.47 and t*peak* durations between 4- and 5-months. Total drought durations appear fairly consistent between both SPI series and the SGI ranging from 15- to 18-months, whilst the SRI is also identifies two phases event duration is shorter at 11-months. Drought severity totals range from -10.20 for the SSI to -22.77 for the SGI, this is the second most severe groundwater drought total in the Derwent Catchment after the 1995-96 event.

5.3.2 Dove Catchment

The Dove catchment drought structure analysis includes SPI-3 and SPI-6 series for the Wall Grange rainfall record, four SSI series (sites 28008, 28018, 28031 and 28046) and one SGI series for the Alstonefield groundwater level data (Figure 5.10). The Alstonefield borehole is located within the catchment of the 28046 streamflow gauge; approximately 50% of this sub-catchment area is underlain by a Carboniferous limestone aquifer. The streamflow gauges included in this analysis are situated at various points within the catchment that include gauges 28031 and 28046 on separate branches in the head waters and the final gauge (28085) on the River Dove before its confluence with the River Trent. SPI*max* values for the SSI and SGI series in this catchment are 2-months (28031, 28008 and 28018), 3-months (28046) and 6-months (Alstonefield).

1975-76

The onset of 1975-76 drought (Figure 5.13a) occurs in the SPI-3, SPI-6 and all SSI values between July and August 1975, whilst in the SGI series drought occurs 4-months earlier in February 1975. Throughout this drought event the SGI series is not synchronous with either the SPI or SSI series; in the two groundwater drought phases identified the d*ons* to d*min* gradients are notably steeper, -1.36 and -1.28 with 3-month t*peak* durations, and d*min* is reached up to 5-months ahead of all other SDI values. The first groundwater drought phase terminates in January 1976 before a second onset phase in February. The key similarity between the SGI and other SDI series is consistent timing of drought termination in October 1976.

The SSI series upstream of the final streamflow gauge in the catchment (28031, 28046 and 28008) have consistent d*ons* to d*min* gradients and t*peak* durations; gradients range from -0.47 to -0.57 with t*peak* durations between 6- and 7-months. These series also have consistent termination gradients and t*term* durations. Despite this similarity, drought onset occurs 2-months later for SSI series 28046. SSI series 28018 (the final streamflow gauge in the catchment) shows more consistency in d*ons* to d*min* and d*min* to d*term* gradients with the SPI-3 and SPI-6 series. Onset characteristics for the 28018 SSI series and both SPI series have d*ons* to d*min* gradients between -0.05 and -0.11, with t*peak* durations between 17- and 20-months. Drought termination characteristics are also consistent between the 28008 SSI series and the SPI series. Despite the differences in drought response noted between the various SDI series, total drought durations are similar across all variables ranging from 14-months (SSI 28046 and SSI 28008) to 19-months (SGI). Severity totals for each SDI series range from -19.50 to -24.76 for all variables excluding the SPI-3 which has a notably lower total at -15.83. During this drought, SSI series for streamflow gauges 28008 and 28018 reach their lowest SSI values (-3.06) in the 1975-2012 analysis period.

1990-92

The 1990-92 drought (Figure 5.13b) is identified as two phases for the SPI and SSI series and three phases for the SGI series. For both phases streamflow drought characteristics appear consistent across all SSI series; the d*ons* to d*min* gradients and t*peak* durations in the onset of the second drought phase range from -0.20 to -0.33 with t*peak* durations from 8- to 10-months. During the second phase SSI d*min* values are reached concurrently in October 1991 with minimum values ranging from -2.33 (28046) to -2.54 (28031, 28008 and 28018). Total drought severity values are also consistent from -11.03 to -13.28 with total drought durations between 10- and 13-months.

Across the three groundwater water drought phases identified, the d*ons* to d*min* gradient of the first phase is the steepest (-2.26) and shortest duration (t*peak* = 2-months); this phase also includes the lowest SGI value (-1.96) for the 1990-92 drought. The total SGI severity across the three phases is -23.10 with a total duration of 19-months, displaying similar SGI characteristics to those identified in the 1975-76 event.

1995-96

The 1995-96 drought (Figure 5.13c) is formed of two drought phases for the SGI, all SSI series and SPI-3. In the first phase, drought onset gradients are consistent between each of the SSI series, with d*ons* to d*min* gradients between -0.35 and -0.41 with t*peak* durations between 8- and 9-months. Despite these similarities in the rate of drought onset occurring, the timing of onset varies from June (28031) to September (28046); the lag on drought onset for SSI series 28046 is consistent with previous drought events. Across the four SSI series d*min* timing occurs between October and November 1995; the timing of d*min* in the SPI-6 also occurs during this period. The d*min* values for SSI series 28046 and 28031 are the lowest (-3.06) in the 1975-2012 period.

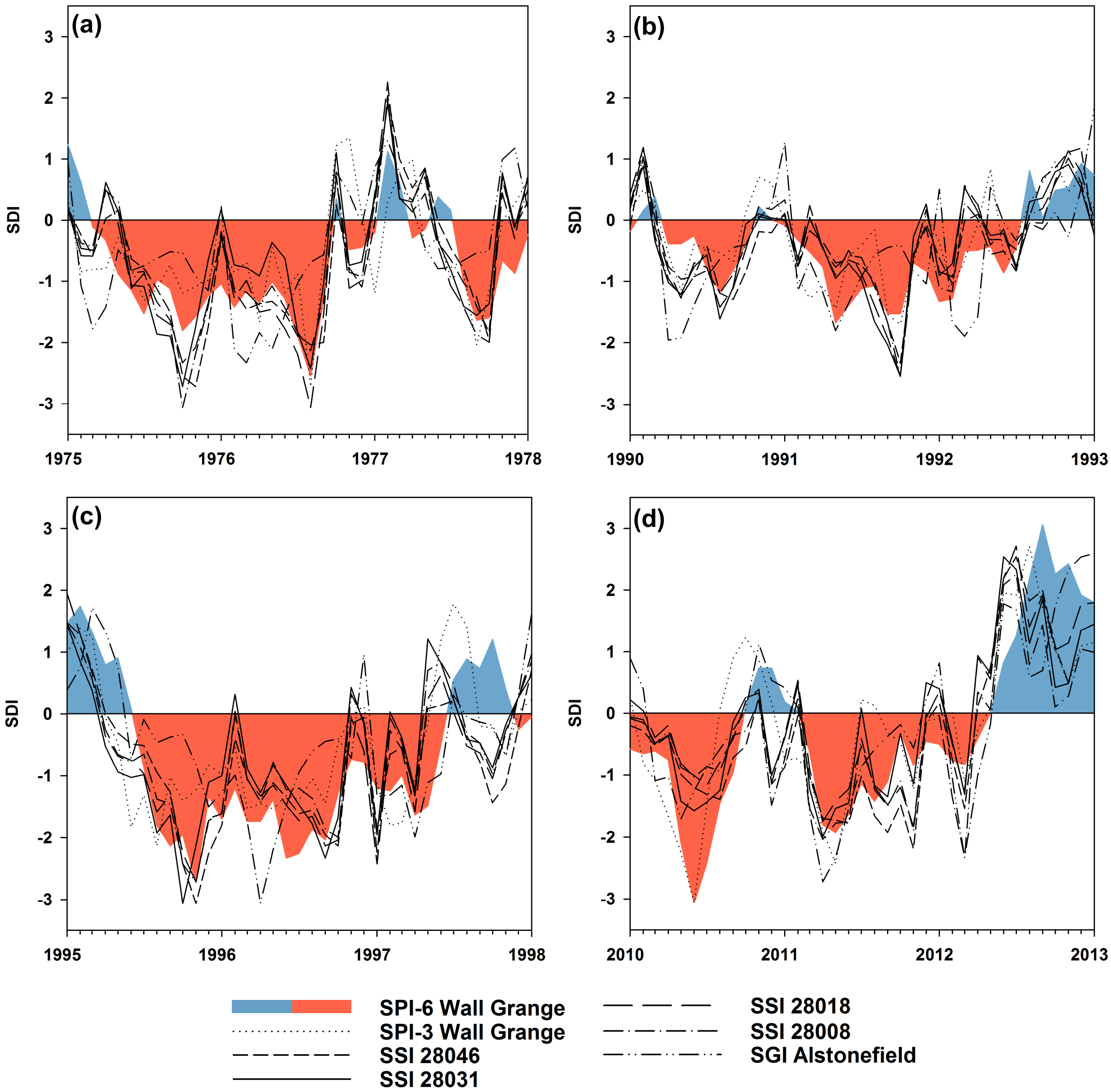

Figure 5.13: SDI plots for the Dove catchment for individual drought events (a) 1975-76, (b) 1990-92, (c) 1995-96, (d) 2010-12

Drought onset characteristics and timing of d*min* for the SGI are different to the SSI and SPI series; the d*ons* to d*min* gradient is -0.22 with a t*peak* duration of 12-months. This is the slowest and shallowest d*ons* to d*min* period across each of the droughts analysed for this groundwater record. Drought onset occurs in December 1995 and the timing of d*min* occurring in the SGI is April 1996, lagging 5-months behind d*min* occurrence in the SPI and SSI series. The SGI reaches a minimum value of -3.06, the lowest SGI value between 1975 and 2012; this is also consistent with the lowest SSI value for 28046 which overlays the aquifer associated with the SGI series. Total drought durations for the SSI series vary from 18- to 23-months with SSI severity totals between -26.89 and -29.21, which is similar to the duration and total SPI severity total for the SPI-3 at 23-months duration and a -27.28 total SPI severity. Drought duration totals and durations are 17-months with a SGI total of -23.16; this is similar to the two previous drought events.

2010-12

The 2010-12 drought (Figure 5.12d) contains the lowest SPI-3 and SPI-6 values (-3.06) in the 1975-2012 analysis period, both occurring in June 2010. During this first drought phase, onset occurs in the SPI-3 and SGI series simultaneously in March 2010 followed by the SPI-6 and SSI series in May and June 2010. Drought termination occurs in all SDI series between August and October 2010. Onset (d*ons*) to SDI minimum (d*min*) gradients appear consistent between the SPI and SGI series (-0.54 to -0.62) and also between the four SSI series (-0.20 – to -0.28). Between November and December 2010 there is discrepancy between the SSI and the SPI values, SSI values are much lower than the corresponding SPI values. This is likely to due to the cold conditions and 'copious' snowfall (Met Office, 2011) experienced across the UK from late November 2010.

The timing of drought onset in the second phase occurs between March and April 2011 for all SDI series. The onset gradients for SSI series 28008, 28031 and 28018 are consistent, ranging from -1.12 to -1.23. This second drought phase is terminated across all SSI and SGI series in December 2011 and January 2012 before onset of the third phase occurring in March and April 2012. By June 2012 the drought is terminated in all SDI series, with values in excess of 2 indicating extremely wet conditions. In the 4-months from March to June 2012 SSI and SGI values increase at a rate of one SDI category per month, which is the most dramatic termination phase across the four droughts examined.

5.3.3 Leadon Catchment

Drought structure in the Leadon catchment is analysed using the SPI based on rainfall data for Taynton, the SSI using streamflow data for gauge 54017 and the SGI computed with groundwater level data for Anthony's Cross. The Anthony's Cross borehole is underlain by a

Permo-Triassic sandstone aquifer that is fully contained within the Leadon catchment (Figure 5.9). SPI*max* results for the SSI and SGI series in this catchment are 3-months and 11-months respectively.

1975-76

Onset of the 1975-76 drought (Figure 5.14a) in the SPI-3, SPI-6 and SSI series in the Leadon catchment occurs in June (SPI-3, SSI) and July 1975 (SPI-6). Drought onset characteristics for the SSI and SPI-3 are the same for the first drought phase, with a -0.70 d*ons* to d*min* gradient and 4-month t*peak* duration. Drought conditions are reached across all SDI series by January 1976. In the SPI-6 series d*min* is reached in April 1976, the SSI and SGI series reach d*min* with a six-month lag in July 1976. Both the SSI and SGI d*min* values during this event are the lowest SDI values (-3.06) in the 1975-2012 analysis period. Based on the SPI-3, SPI-6 and SSI drought termination occurs in September 1976. By October 1976 the SPI-3 and SSI reach values >2.00 indicating very wet conditions. Groundwater drought persists into 1977 terminating in February, 5-months after termination in other SDI series. Total drought duration varies from 11-months for the SPI-3 to 14-months for the SPI-6 and SSI series. Both the d*min* and total severity values for the SPI-3 are higher than the other SDI values; d*min* is -1.96 and total severity is -16.95, the SPI-6, SSI and SGI have d*min* values between -2.54 (SPI-6) and -3.06 (SGI) and drought severity totals between -20.55 (SGI) and -25.94 (SSI).

1990-92

The 1990-92 drought (Figure 5.14b) is formed of two phases for the SPI and SSI; drought onset of the initial phase occurs first in the SSI (April 1990) followed by the SPI-3 (May 1990) and the SPI-6 (July 1990). The onset (d*ons*) to drought minimum (d*min*) gradient for the SPI-3 is steep (-2.34); with a 2-month t*peak* duration this is the fastest drought onset across all droughts analysed for the SPI-3 in this catchment. In this first phase, d*min* values for the SPI-3 and SSI occur simultaneously in May 1990, followed by the SPI-6 in August 1990. Hydrological drought duration is shorter than meteorological drought duration (9-months) with drought termination occurring in January 1991. Meteorological drought persists into the spring and summer terminating in April (SPI-3) and July (SPI-6). Groundwater drought onset occurs in August 1991, after drought conditions have terminated in the other SDI series. The two phases identified in the SPI and SSI series are manifest as a single groundwater drought. The d*ons* to d*min* gradient is notably shallower (-0.04) with a longer t*peak* duration (24-months) than the SSI and SPI drought onset characteristics.

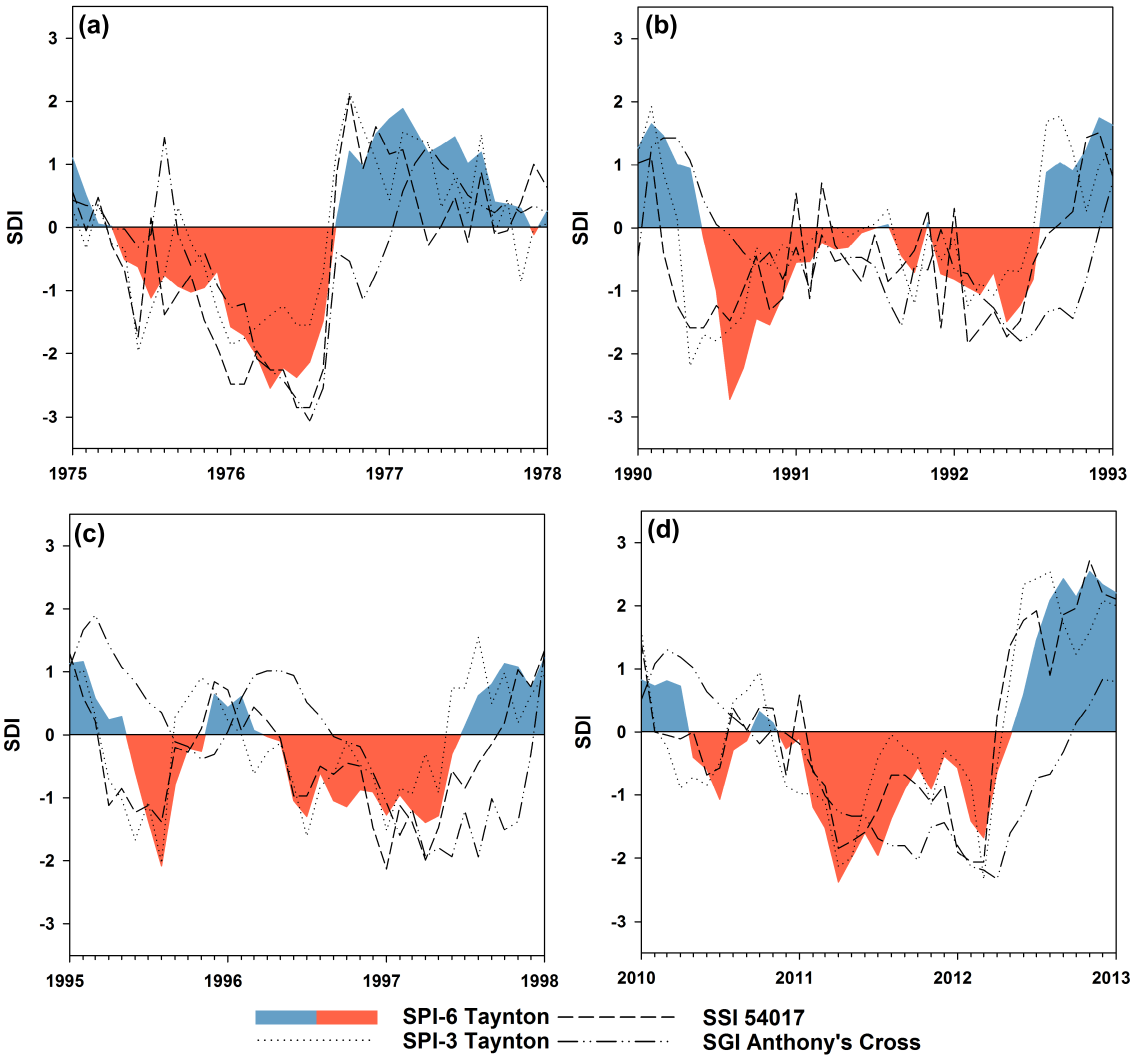

Figure 5.14: SDI plots for the Leadon catchment for individual drought events (a) 1975-76, (b) 1990-92, (c) 1995-96, (d) 2010-12

The second drought phase occurs first in the SPI-3 series (October 1991) followed by the SSI in February 1992 and the SPI-6 in March 1992. Both meteorological drought and hydrological drought terminate in July (SPI-3) and August 1992 (SPI-6 and SSI) Groundwater drought conditions persist throughout 1992 (from onset in July 1991) terminating in January 1993. During this second drought phase d*min* occurs during February 1992 for the both the SPI-3 and SSI, followed by the SPI-6 in May 1992 and the SGI in June 1992. Despite the differences in drought characteristics between the SPI/SSI and the SGI series total drought duration and drought severity are consistent across the SDI series.

Drought severity totals range from -17.09 (SPI-3) to -19.58 (SSI) with total durations between 16- and 17-months for the SPI-6, SSI and SGI and 21-months for the SPI-3.

1995-96

Results of the meteorological drought analysis in Chapter 4 reveals that the 1995-96 drought is least severe in the south-west of the STR, including the Leadon catchment. The SDI plot for this drought event (Figure 5.14c) shows two distinct drought phases, the first during the spring and summer of 1995 and the second from summer 1996 into summer 1997. Drought onset in the first phase occurs in April 1995 (SSI), May 1995 (SPI-3) and July 1995 (SPI-6); during this phase there are no drought conditions observed in the SGI series. The SPI-3, SPI-6 and SSI all reach d*min* in August 1995, with event termination between September (SPI-3) and December 1995 (SPI-6). Drought onset (d*ons*) to d*min* gradients are consistent between the SPI-3 (-0.38) and SSI (-0.23) with 6-month t*peak* durations.

During the second event phase the onset and termination of meteorological drought conditions occur considerably ahead of hydrological and groundwater drought. Meteorological drought onset occurs during June (SPI-6) and July (SPI-3)1996, hydrological and groundwater drought onset occurs with a lag of 6- and 7-months in December 1996 (SSI) and January 1997 (SGI). Event termination occurs in the SPI series in June (SPI-3) and July 1997 (SPI-6). Whilst the SSI and SGI enter drought conditions within 1-month termination characteristics are not as consistent. Termination occurs in the SSI series in October 1997 followed by the SGI in January 1998. Despite the variation in drought onset and termination characteristics across the SDI series, drought durations are similar, ranging from 10-months (SSI) to 13-months (SPI-6).

2010-12

In the Leadon catchment this drought event only occurs across all SDI series in 2011 and 2012 (Figure 5.14d). The SPI-6 series identifies a 3-month meteorological drought between July and September 2010. Drought onset in 2011 occurs between February (SPI-6) and April (SSI); unlike the previous droughts examined groundwater drought onset precedes hydrological drought onset. Drought onset characteristics for the SPI-3, SSI and SGI are consistent; d*ons* to d*min* gradients range from -0.03 (SPI-3) to -0.12 (SGI) with t*peak* durations between 15- and 18-months. SDI minimum values (d*min*) for the SPI-3, SSI and SGI occur between March (SPI-3 and SSI) and April (SGI) 2012. However, the slower response of the SGI identified in the previous droughts examined is observed between

August and November 2011; where SPI and SSI values increase the SGI continues to decrease.

Drought termination for the SPI and SSI series is rapid; d*min* to d*term* gradients for the SPI-3 and SSI are steep at 1.58 with a 3-month term duration and a 2.31 gradient with a 2-month t*peak* duration respectively. Hydrological drought terminates in April followed by the SPI-3 in May and SPI-6 in June 2012. Groundwater drought termination lags considerably behind occurring in October 2012. Across all the SDI series d*min* values are all less than -2.00 reaching the extreme drought classification. Event severity totals vary considerably, -13.01 (SPI-3), -19.09 (SPI-6), -1659 (SSI) and -28.24 (SGI), and drought durations vary by up to 6-months due to the lag in groundwater drought termination ranging from 13- (SSI) to 19-months (SGI).

5.3.4 Teme Catchment

The Teme catchment (Figure 5.9) is located in the south-west of the STR and is the largest catchment included in this analysis with a 'natural' flow regime at 1480km^2. Drought structure analysis for this catchment includes SPI series for the Oakly Park rainfall record and two streamflow datasets for the River Teme, streamflow gauges 54008 and 54029. Streamflow gauge 54029 is the final gauge on the River Teme before its confluence with the River Severn. This catchment is predominantly rural with grassland forming approximately 60% of the land cover and the geology is predominantly low permeability. SPI*max* results in the previous section (5.2) for the 54008 (SPI*max* = 2-months) and 54029 (SPI*max* = 3-months) indicate a quick hydrological response to meteorological conditions.

1975-76

The onset of the 1975-76 drought (Figure 5.15a) occurs simultaneously for the SPI series and SSI 54029 (June 1975) followed by the SSI 54008 in August 1975. Throughout this drought event, the two SSI series exhibit some varying drought behaviour; the d*ons* to d*min* gradients are -0.14 (54008) and -0.38 (54029) with t*peak* durations of 7- (54008) and 18-months (54029). The timing of SSI minimum values varies by 10-months, occurring in October 1975 for the SSI 54008 and in August 1976 for SSI 54029. The timing of d*min* for SSI 54029 is more consistent with the d*min* timings for the SPI-3 and SPI-6 which both occur in June1976. Despite the differences in drought onset and d*min* timing between the SSI 54008 and other SDI series, drought termination is consistent across all SDI values occurring in September 1976. Drought termination is rapid, particularly for the SSI 54029 and SPI-3 with d*min* to t*term* gradients of 4.19 and 1.23 and t*term* durations of 2- and 4-months respectively. Despite some variation in the timing of onset and d*min* between the SSI series total event duration is consistent between all SDI series ranging between 13- (SPI-3 and SSI 54012) and 15-months (SPI-6 and SSI 54008).

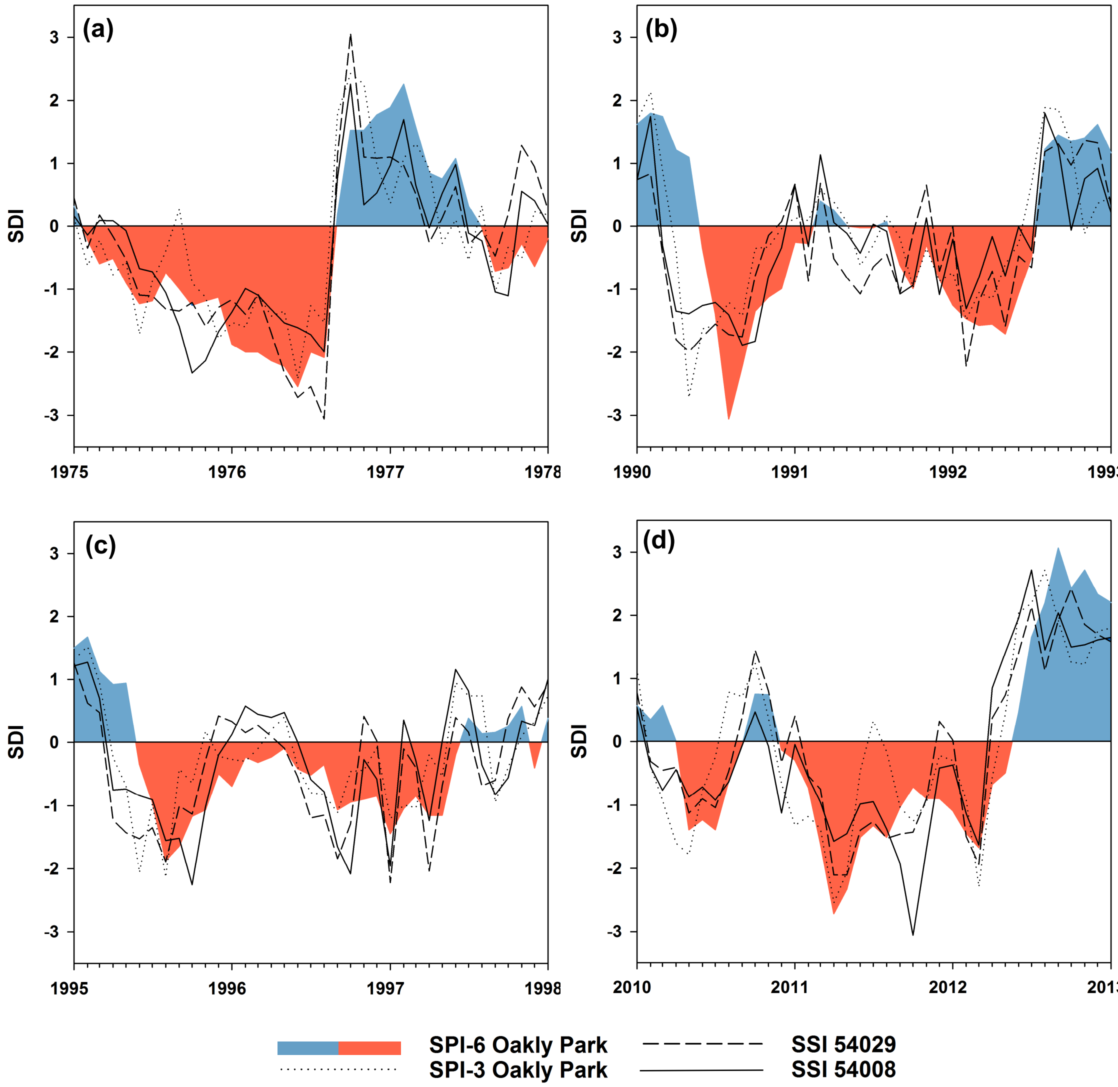

Figure 5.15: SDI plots for the Teme catchment for individual drought events (a) 1975-76, (b) 1990-92, (c) 1995-96, (d) 2010-12

1990-92

The 1990-92 drought (Figure 5.15b) is formed of multiple drought phases; the SPI-3 and SPI-6 have two phases, whilst the SSI 54029 and SSI 54008 have three phases. Hydrological drought onset occurs first (April 1990) followed by the SPI-3 (May 1990) and the SPI-6 (July 1990). Drought onset to d*min* gradients vary between the each of the SDI series, ranging from -1.70 (SPI-3) to -0.36 (SSI 54029) with t*peak* durations between 5- and 8-months. Timing of d*min* varies between the SDI series; during the first drought phase, the SPI-3, SPI-6 and 54008 all reach minimum SDI values for the entire 1990-92 drought analysis period whereas the SSI 54029 reaches d*min* in its third drought phase. Between June and September 1991 hydrological drought is observed in both SSI series, which is not reflected in the meteorological conditions. The second meteorological and third hydrological drought phase onset occurs between December 1991 and February 1992 with onset observed first in SSI 54029. Termination occurs between August (SPI-3) and September 1992 (SPI-6, SSI 54008 and SSI 54029). Despite some the differences observed between the SDI series, the event durations of the two phases identified in all SDI series are consistent, ranging between 8- and 9-months for the first phase and 5- and 6-months for the last phase.

1995-97

Examination of the 1995-97 drought (Figure 5.14c) identifies varying characteristics between each of the SDI series; a key example of this is the number of drought phases observed. The SPI-6 series identifies a single drought phase between August 1995 and July 1997, whilst the SPI-3 identifies two phases (June to October 1995 and September 1995 to June 1997) and the SSI both have three drought phases. Across the three hydrological drought phases only the first phase has consistent drought onset to SSI minimum gradients (-0.32 and -0.35) and t*peak* durations (6- and 8-months); however, the timing of onset varies from April 1995 (SSI 54029) to August 1995 (SSI 54008). Across the three drought phases total drought duration and severity values for the two SSI series differ, with durations between 11- and 17-months and severity totals between -14.31 and -20.71 for gauges 54008 and 54029 respectively. Totals duration and severity for the SPI series range between 14- (SPI-3) and 23-months (SPI-6), with severity totals between -12.27 (SPI-3) and -18.64 (SPI-6).

2010-12

Like the 1995-97 drought, the 2010-12 drought (Figure 5.14d) is formed of a differing number of drought phases between the SDI series. The SSI 54008 identifies a single drought, the SPI-6 identifies two drought phases and the SPI-3 and SSI 52029 both exhibit three drought phases. In the SPI-3, SPI-6 and SSI 54029 series a moderately severe drought is identified between April and September 2010. Hydrological drought onset for streamflow gauge 54008 occurs in December 2010 followed by the onset of the second meteorological drought phase for the SPI-3 in January 2011 and the SPI-6 in March 2011; the second drought phase of the SSI 54029 occurs in April 2011. Due to the various drought phases identified across the SDI series, d*ons* to d*min* gradients and t*peak* also vary. Minimum SDI values for the SPI-3, SPI-6 and SSI 54029 are all reached simultaneously in April 2011, whilst d*min* for the SSI 54008 occurs in October 2011. Total drought durations range from 18- to 20-months for the SPI-3 and SPI-6 respectively, and from 13- to 15-months for the SSI 54008 and SSI 54029 series.

5.3.5 Tern Catchment

The Tern catchment is located in the north-west of the STR (Figure 5.9), with an area of 852km^2 the catchment includes the headwaters of the River Tern and the River Roden. Approximately 25% of the catchment is underlain by a Permo-Triassic sandstone aquifer. This drought structure analysis includes SPI series for the Weston Park rainfall record, SSI series for the 54016 and 54012 streamflow gauges and an SGI series for the Heathlanes observation borehole. Streamflow gauge 54016 is situated on the River Roden and 54012 is situated on the River Tern immediately after the confluence of the Roden and the Tern. In the previous section the SPI*max* for both the Roden and the Tern is 5-months.

1975-76

Onset of 1975-76 drought (Figure 5.16a) in the Tern catchment occurs first in the two SSI series in June 1975 followed by the SPI-3 and SPI-6 series in October 1975. Groundwater drought onset lags behind meteorological and hydrological drought onset by 5- and 9-months respectively. Despite the observed lag in the timing drought onset, d*ons* to d*min* gradients are consistent across all SDI series, ranging between -0.07 (SPI-3) and -0.12 (SSI 54012) with t*peak* durations between 16- and 19-months. All of the SPI and SSI series reach d*min* in August 1976 with values <-2.00. The SGI reaches d*min* (-1.87) one month later in

September 1976. Meteorological and hydrological drought termination is rapid; d*min* to d*term* gradients are in excess of 2.00 with 2-month t*term* durations for the SPI-3 and both SSI series. Groundwater drought termination occurs over 35-months (from d*min* to t*term*), terminating in August 1979. All drought characteristics are consistent between the SSI, including event duration (15-months) and total severity (-19.30).

1990-92

The 1990-92 drought (Figure 5.16b) is formed of two phases across all SPI and SSI series. In the first drought phase, drought onset occurs first in the SSI series in April followed by the SPI-3 in May and SPI-6 in July 1990. During this phase no groundwater drought is observed. The timings of event onset and termination are consistent between the SPI-3 and two SSI series with termination occurring in December 1990. Between May and September 1991 drought is identified in SSI 54012 which is not seen in any other SDI series. Onset of the second drought phase for the SPI-3, SPI-6 and SSI 54016 occurs between October (SPI-3) and December 1991 (SPI-6 and SSI 54016). Groundwater drought onset lags between 3- and 5-months behind the SPI-6, SSI 54016 and SPI-3 respectively, occurring in March 1992.

SDI minimum values for the SPI and SSI series are all reached simultaneously in February 1992 and d*ons* to d*min* gradients are consistent, -0.12 (SPI-3 and SSI 54012) and -0.15 (SPI-6 and 54016). For the SGI series d*min* is reached in August 1992, 6-months after the SPI and SSI series. Drought termination for the SPI series varies between May (SPI-3) and July 1992 (SPI); hydrological drought termination occurs first for SSI 54016 (June 1992) followed by 54012 in August 1992. The slow response of the Permo-Triassic sandstone aquifer results in groundwater drought termination in September 1994 resulting in a total drought duration of 30-months. Meteorological drought durations are 14- (SPI-3) and 16-months (SPI), and due to the early onset of drought conditions for the SSI 54012, hydrological drought duration varies between 14- (SSI 54016) and 23-months (SSI 54012).

1995-95

From a meteorological perspective, the onset to minimum SPI values of the 1995-96 drought (Figure 5.16c) occurs rapidly; d*ons* to d*min* gradients are -0.72 (SPI-3) and -1.22 (SPI-6) with t*peak* durations between 4- (SPI-6) and 6-months (SPI-3) with minimum SPI values reached in August 1995. Minimum SPI values reach -3.06, the lowest across the 1975-76 analysis period. Whilst both meteorological and hydrological drought onset occurs between June

(SPI-3 and SSI) and July (SPI-6) 1995, hydrological drought onset to minimum SSI characteristics are not consistent with the SPI. Minimum SSI values are reached in April 1997 resulting in d*ons* to d*min* gradients of -0.02 and -0.06 with t*peak* durations of 24- and 28-months. Groundwater drought onset occurs in March 1997, 21-months after onset for the SPI-3 and SSI series and d*min* is reached in September 1997. This results in a d*ons* to d*min* -0.10 gradient with a 23-month t*peak* duration which is similar to the onset characteristics for the SSI series. Drought termination for the SPI-3, SPI-6 and SSI 54012 occurs in June 1997, followed by the SSI 54016 in October 1997. Groundwater drought termination occurs in December 1999. Drought durations and severity totals are consistent for the SPI and SSI series, ranging from 23- (SPI-6) to 28-months (SSI 54016) with severity totals between -22.64 (SPI-3) and -29.89 (SPI-6). The duration of groundwater drought is 33-months with a -31.98 severity total.

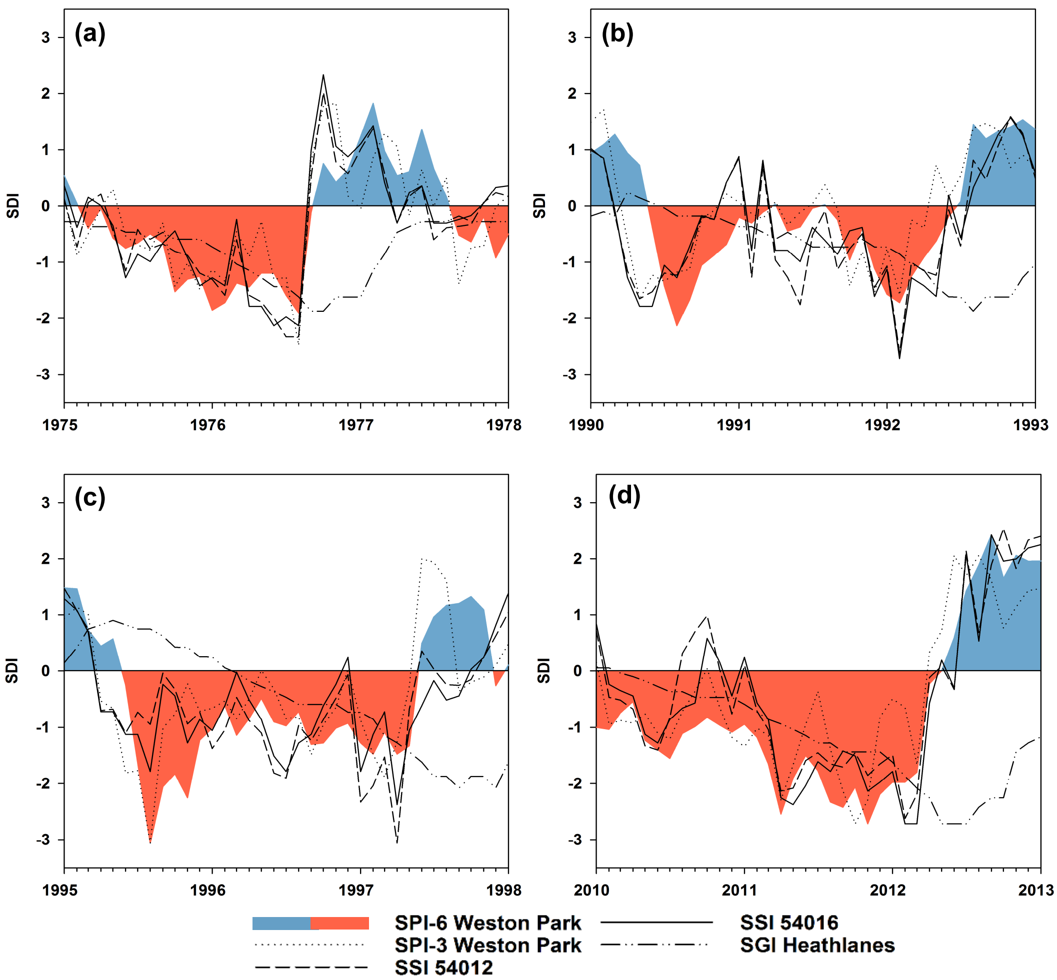

Figure 5.16: SDI plots for the Tern catchment for individual drought events (a) 1975-76, (b) 1990-92, (c) 1995-96, (d) 2010-12

2010-12

The 2010-12 drought (Figure 5.16d) is formed of two drought phases based on the SPI-3 and two SSI series, and one drought phase based on the SPI-6 and SGI series. Drought onset and termination timing and characteristics vary between each of the SDI series; onset of the first phase of hydrological drought occurs in May 2010 for both SSI series and June 2010 for the SPI-3, onset occurs earlier for the SPI-6 series in February 2010. Drought termination for the SSI 54012 series occurs in August 2010 followed by the SSI 54016 and SPI-3 in October 2010. Drought characteristics across the SDI are variable, the timing of onset for the SPI-3 is December 2010 whereas hydrological drought onset is March (54016) and April (54012) 2011 and groundwater drought in May 2011. The timing of d*min* across the SDI series ranges from October and November 2011 for the SPI-3 and SPI-6 respectively, February 2012 for the SSI series and May 2012 for the SGI. Drought termination for the SPI and SSI series occurs between April (SPI-3) and May (SPI-6 and SSI) 2012. Groundwater termination is not reached before the end of the analysis period in December 2012. Despite the observed variations in the timing of d*min*, the values are consistent across all SDI series ranging from -2.62 (SSI 54012) to -2.72 (SPI-3, SPI-6, SSI 54016 and SGI).

5.3.6 Wye Catchment

Examination of drought structure in the Wye catchment is focused in the headwaters of the River Wye which also contain the Elan Valley reservoir group. Variables includes in this analysis are the SPI for the Rhayader rainfall series, the SSI for streamflow gauge 55026 and the SRI for the Elan Valley reservoir group. Streamflow gauge 55026 is the lowest gauge on the Wye that is not influenced by the Elan Valley reservoirs. SPI*max* results for the SSI and SRI are 1-month and 5-months respectively.

1975-76

The 1975-76 drought (Figure 5.17a) is formed of two drought phases for the SPI-3 and SSI series and one drought phase for the SPI-6 and SRI series. Drought onset occurs first in the SPI-3 series (April 1975), followed by the SPI-6 and SSI in June 1975 and the SRI in July 1975. Event termination for the SPI-3 and SSI occurs in September 1975, whilst drought persists in the SPI-6 and SRI series. For the first drought phase, onset and termination gradients for the SPI-3 and SSI are consistent, d*ons* to d*min* gradients are-0.47 and -0.33 and d*min* to d*term* gradients are 0.64 and 0.56 for the SPI-3 and SSI respectively. Onset of the second drought phase for the SPI-3 and SSI occurs in December 1975 and April 1976 respectively. The timing and value of d*min* across all the drought phases is coherent for the SPI-3, SPI-6 and SSI, reaching -3.06 in August 1976; this is the lowest SDI value for each variable in the 1975-2012 analysis period. The minimum SRI value has a 2-month lag behind the other SDI series occurring in October 1976. Drought termination for the SPI-3 and SSI is simultaneous, occurring October 1976, followed by the SPI-6 and SRI in February and March 1977. Total drought durations vary from 9- (SSI) to 20-months (SPI-6 and SRI) and severity totals range from -32.24 (SPI-6) to -14.19 (SSI).

1990-92

As identified in Chapter 4, the 1990-92 drought (Figure 5.17b) is least severe in the west of the STR; meteorological drought conditions are only identified for 2- (SPI-6) and 3-months (SPI-3) between May and September 1992. Hydrological drought conditions for the SSI series are consistent with the meteorological drought, occurring between April and June 1990. Drought durations for the SPI and SSI series ranges from 2- to 3-months with severity totals between -3.25 and -3.76. The SRI series has the most severe and longest duration drought, lasting for 9-months with a -11.20 severity total.

1995-96

The 1995-96 drought (Figure 5.16c) occurs in two phases for the SSI and SRI, and a single phase for the SPI-3 and SPI-6. Drought onset varies over a 4-month period, occurring first in the SSI series (April 1995), followed by the SPI-3 (June 1995), the SRI (July 1995) and the SPI-6 (August 1995). Minimum SDI values for the SPI-3 and SSI are reached simultaneously in August 1995 followed by the SPI-6 in September 1995 and the SRI in November 1995.

Termination of the first drought phase for the SSI and SRI occurs in May 1996, onset of the second phase occurs between July (SSI) and September 1996 (SRI). Termination of meteorological drought occurs in October and November 1996 for the SPI-3 and SPI-6 respectively, drought termination for the SSI also occurs in October 1996. Drought termination of the SRI lags behind the other SDI variables, terminating in May 1997. Total drought severity is notably more severe for the SRI series (-24.11), severity totals for the SPI-3, SPI-6 and SSI ranging from -8.96 to -14.11.

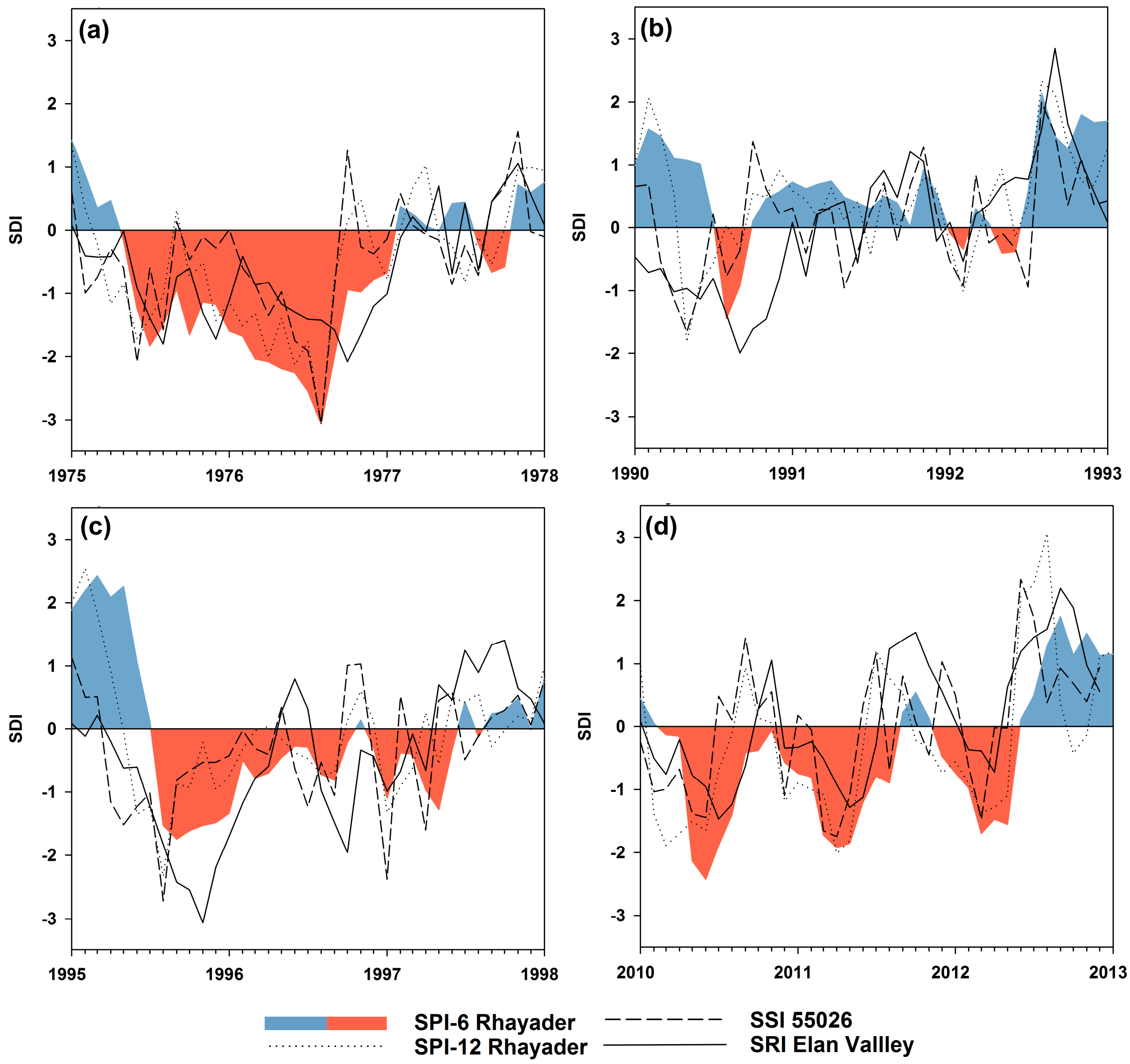

Figure 5.17: SDI plots for the Wye catchment for individual drought events (a) 1975-76, (b) 1990-92, (c) 1995-96, (d) 2010-12

2010-12

The 2010-12 drought (Figure 5.16d) consists of two phases for the SPI-6 and SRI, and three series for the SPI-3 and SSI. Across the SDI series, drought onset varies over a 6-month period, occurring first in February 2010 (SPI-3 and SSI), followed by the SPI-6 in May 2010 and the SRI in July 2010. Drought onset in the SRI series occurs during the same month as drought termination in the SSI series. Meteorological drought is notably more severe than hydrological drought; severity totals for the SPI series are -20.85 and -23.88 compared with SSI and SRI severity totals at -11.54 (SSI) and -6.01 (SRI). Minimum SDI values (d*min*) for the SPI-3 and SPI-6 are both <2.00 whereas the SRI and SSI d*min* values are -1.74 and -1.47

respectively. Meteorological drought duration is longer than hydrological drought duration at 17-months compared to 6- and 11-months for the SRI and SSI respectively.

5.3.7 Synthesis of Drought Structures

Examination of the structure of individual drought events coupling meteorological, hydrological and hydrogeological datasets at the catchment scale provides interesting insight into the relationships between meteorological, hydrological and groundwater droughts. Notable results from the analysis presented in the previous sub-sections include-

1) The most severe meteorological droughts do not necessarily result in the most severe hydrological or groundwater droughts. This is observed in the Derwent catchment where the both the SPI-3 and SSI reach the lowest SDI in the 1975-77 drought but the lowest SGI values are reached during the 1995-97 drought.
2) In the Derwent catchment, total severity values for the SPI and SSI are twice the severity total of the SGI series for the 1975-77 drought. This is not observed in the other drought events in the Derwent catchment.
3) For the SGI series in both the Dove and Derwent catchments, all groundwater droughts are characterised in at least two phases. Drought termination tends to occur over winter in either November, December, January or February.
4) In the Derwent catchment, groundwater drought onset and termination characteristics for 1975-76, 1990-92 and 2010-12 droughts show that d_{ons} to d_{min} gradients of the second drought phase is steeper and quicker with t_{peak} durations ranging between 2- and 3-months.
5) In the Dove and Leadon catchments, hydrological drought total severity values for the 1975-77 drought are more consistent with the SPI-6 severity totals than those for the SPI-3 even though all of the SSI series have SPI_{max} values between 2- and 3-months. SPI_{max} durations of 2- and 3-months suggests that the SSI series should have similar drought characteristics to the SPI-3.
6) Across the four SSI series within the Dove the timing of the lowest SSI value in the 1975-2012 analysis period is not consistent. At streamflow gauges 28008 and 28018 the lowest SSI value both occur during the 1975-77 drought whereas, gauges 28031 and 28046 reach the lowest SSI values during the 1995-97 drought.

7) Each groundwater drought in the Dove catchment has similar drought duration and severity characteristics. Drought durations range from 17- to 20-months with severity totals between -22.11 and -23.16. These characteristics are more variable for the SPI and SSI series.
8) The lag between meteorological drought onset and groundwater drought water drought is not consistent between drought events, in the Leadon catchment the lag between onset for the SPI-6 and the SGI is 6-months in contrast to a 1-month lag for the 2010-12 drought.

5.4 The Climatic Drivers of Drought

This section analyses the relationship between atmospheric circulation indices and the SPI-12 across the STR. Three atmospheric circulation indices are used in this analysis- the Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO) and the East Atlantic-Western Russia (EA-WR). The monthly values for each of these atmospheric circulation indices are averaged over the previous 11-month period to provide a consistent timescale with the SPI-12, based on Vicente-Serrano et al. (2015). A 60-month (5-year) centred moving window correlation is calculated between each circulation index and the SPI-12. Using the moving window correlation approach allows for the examination of the links between large scale climate drivers and the SPI that considers the temporal variability of the climate drivers. The moving window or running correlation method is commonly applied to assess the variation in the relationship between climate series (Slonosky et al., 2001). As a result of the multiple comparisons problem (Abdi, 2007) a statistically significant relationship between an atmospheric circulation index and the SPI is based on modified p-value at the 0.05 significance based on the Bonferroni Correction (Abdi, 2007).

Both the AMO and NAO indices are available from the mid-19th Century allowing for a long series analysis with the SPI-12 from 1865-2012 for the three longest rainfall records in the STR and a mean SPI-12 of these three rainfall records. The EA-WR circulation index is available from 1951-2012 and examined with SPI-12 series for nine rainfall series; eight rainfall records are those used in long series meteorological drought analysis and a mean rainfall series for all eight datasets. The NAO and AMO are also included in a 1951-2012 analysis. An investigation of the links between large scale climate drivers and the SPI may provide insight for the potential to attribute specific drought characteristics identified, such as rapid onset or termination times as identified in the 1975-77 and 2010-12 droughts, to specific climate drivers. A better understanding of the relationship between climate drivers and the SPI may also be beneficial for the development of drought monitoring and early warning systems that utilise SDIs.

5.4.1 Long Series Analysis SPI-12 with the NAO and AMO (1860-2012)

This subsection focuses on the relationship between the SPI-12 with the AMO and NAO in the STR from 1860-2012.

AMO

The AMO index is derived from North Atlantic sea surface temperatures which modulate between cooler and warmer phases over an interdecadal time period. Cooler (negative) phases of the AMO were observed during the 1890s to mid-1920s and mid-1960s to the late-1990s (Figure 5.17). Typically, negative AMO conditions are associated with reduced precipitation across the UK (Met Office, 2014). Plots for the SPI-12 and AMO, and results for the 60-month moving window correlations for the STR are presented in Figure 5.17. The 'long drought' (1890-1910) and the 1921-23 drought both correspond with a negative phase of the AMO index between 1890 and 1925. A number of drought phases during this period present positive correlations between the SPI-12 and AMO, however, these results are not significant at the 0.05 level. The only statistically significant correlation identified in this period is for the Weston Park SPI-12 series between 1905 and 1908.

During a negative AMO phase between the mid-1960s and late-1990s, a number of meteorological droughts are identified including the 1975-77 and 1990-92 events. However, there are no significant positive correlations between the AMO and SPI-12 for the 1975-77 drought and only SPI series for Weston Park is significantly correlated with the 1990-92 drought. The 1995-97 drought occurs during a transition in the AMO from negative to positive. The only drought phase observed across the STR that is significantly correlated with a negative phase of the AMO is the 1862-65 drought. During this phase the negative AMO and negative SPI are significantly correlated between May 1862 and June 1865. This negative phase of the AMO occurs during a period where positive AMO value are more dominant between 1854 and 1890. Despite the notion that reduced precipitation is associated with a negative AMO, a number of droughts are identified during positive AMO phases including the 1933-35, 1942-46 and 2010-12 event. At Rhayader, the 1933-35 drought is significantly negatively correlated with the AMO.

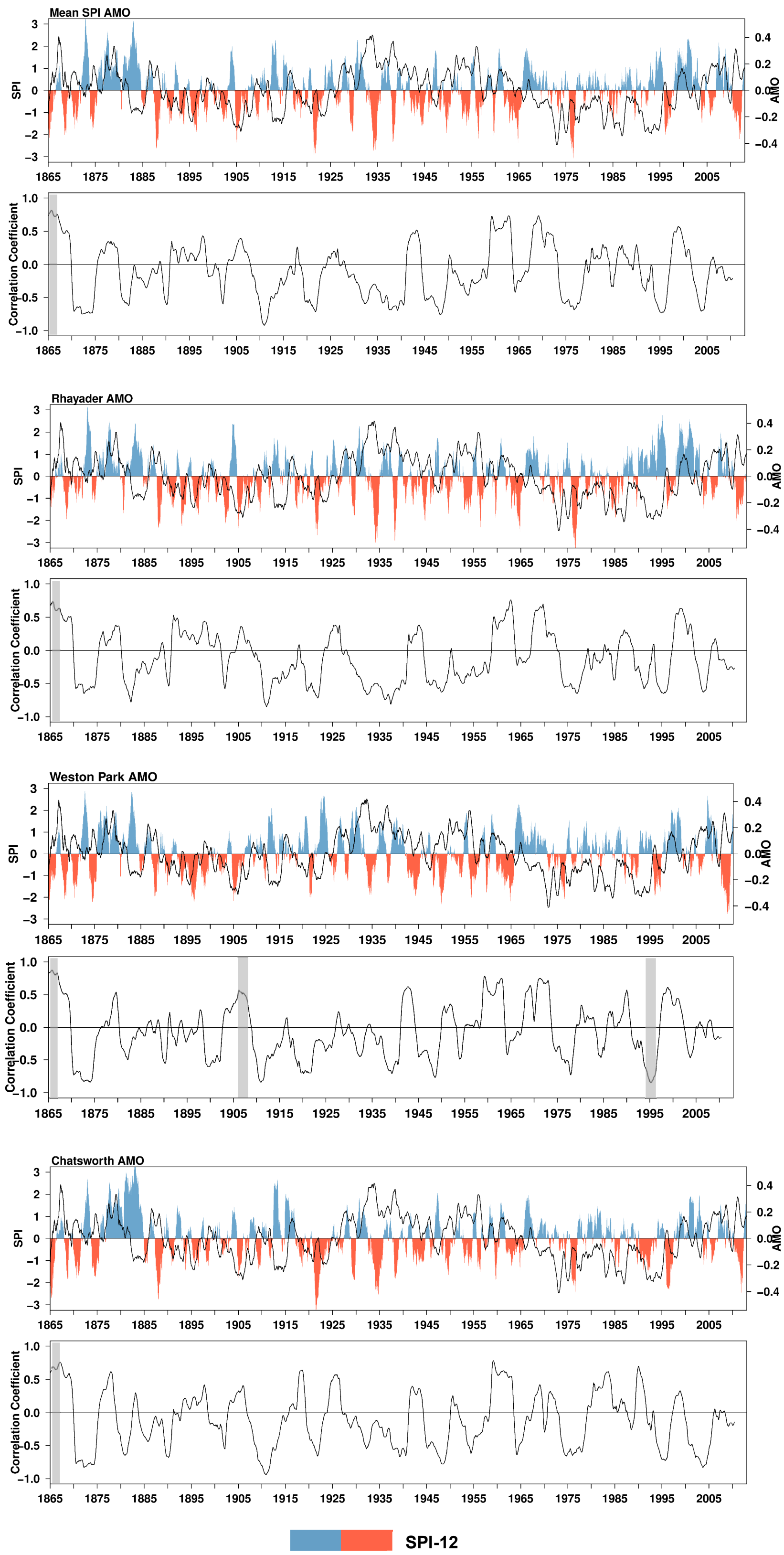

Figure 5.18: Plots for the SPI-12 and AMO index with associated 60-month moving window correlation coefficients. Grey boxes identify drought periods significantly positively or negatively correlated with the AMO.

NAO

The NAO is one of the dominant teleconnections linked to climatic variability across Europe. The NAO index is derived from the normalised difference of atmospheric pressure observations at sea-level between Iceland and the Azores/Gibraltar. Typically, negative NAO values are associated with colder and drier winters in the UK due to the suppression of westerly storm tracks, whilst positive NAO values are linked to mild and wet winters.

Results for the moving window correlation analysis between the NAO index and the SPI-12 (Figure 5.18) find negative NAO values correspond with the 1887-89, 1902-03, 1995-97 and 2010-12 droughts with significant positive correlations at the 0.05 level across all four SPI-12 series. The Rhayader SPI series, located in the Welsh uplands, has eight drought phases that are significantly correlated with the NAO compared to four significantly correlated phases identified for the Weston Park and Chatsworth SPI series.

A number of major meteorological droughts occur when the NAO is positive including the 1921-23, 1975-77 and 1990-92 events. At Weston Park, the 1869-70, 1975-77 and 1990-92 droughts are significantly negatively correlated with the NAO index at the 0.05 level. During the 'long drought' NAO index values are predominantly positive excluding a drought phase from 1902-03.

Table 5.6: Meteorological droughts and associated climate drivers (NAO and AMO) from 1860-2012.

Meteorological Drought	Associated Climate Driver
1862-65	AMO
1887-89	NAO
1905-07 (Weston Park)	AMO
1901-1903	NAO
1995-97	NAO
2010-2012	NAO

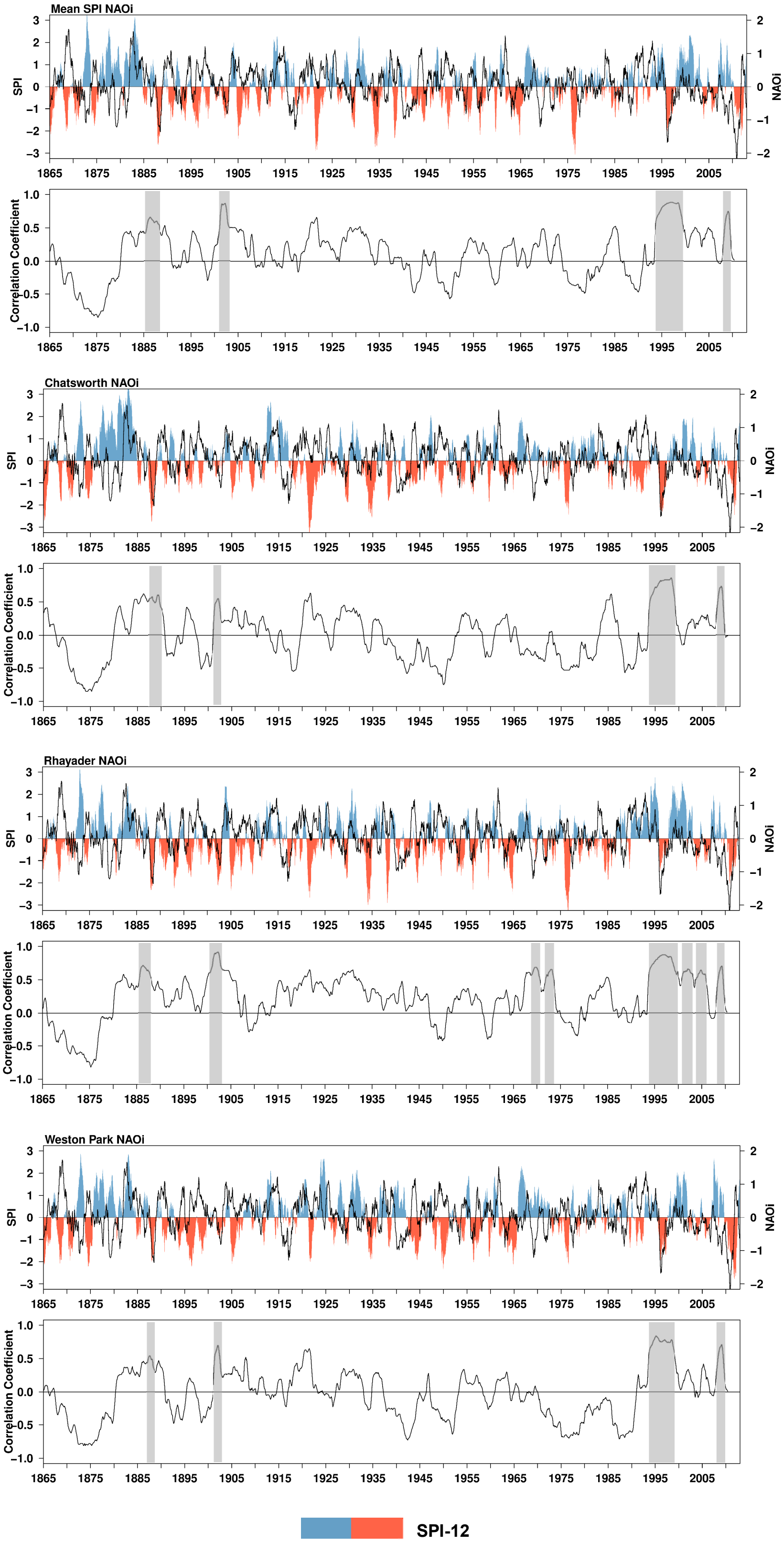

Figure 5.19: Plots for the SPI-12 and NAO index with associated 60-month moving window correlation coefficients. Grey boxes identify drought periods significantly correlated with the NAO.

5.4.2 AMO and NAO (1951-2012)

AMO

Moving window correlation analysis for the SPI-12 and the AMO across the STR (Figure 5.18) identifies no significant correlations between meteorological drought and negative AMO values between 1951 and 2012. As outlined in the long series analysis of the SPI and AMO whilst there are drought events identified during negative AMO phase from the mid-1960s to the mid-1990s there are no significant correlations between them. During the 1975-77 drought negative significant correlation is identified between the AMO and SPI-12 series for a number of the rainfall series including the STR mean SPI-12 series. AMO values are increasing whilst the SPI values are decreasing; however, during this time the AMO values remain negative. A number of drought events are identified during positive AMO phases including 1955-57, 1959 and 2010-12.

NAO

All SPI-12 series used in this analysis show significant positive correlations between the SPI-12 and NAO index for the 1995-97 and 2010-12 droughts (Figure 5.19). Other drought events are also highly correlated with the positive NAO index for individual SPI series. This includes the 1962-65 drought at Wall Grange and minor drought events in 1973, 1984, 2003 and 2005-06 at Rhayader. The NAO index is negative during the first year (1962-63) of the 1962-65 drought but, no significant correlation is identified in this period.

5.4.3 EA-WR (1951-2012)

The EA-WR is a teleconnection pattern based on two anomaly centres, one located over the Caspian Sea and one over Western Europe. Positive phases of the EA-WR are associated with low pressure over western Europe and south-western Russia and high pressure over north-western Europe, resulting in drier than average conditions over Europe.

Results of the moving correlation analysis between the SPI-12 and EA-WR for rainfall records across the STR identify significant negative correlation coefficients between positive EA-WR values and negative SPI-12 values for the 1975-76 drought (Figure 5.19). Whilst this pattern is identified at Wall Grange, the correlation coefficient is not significant. The later stages of the 1962-65 drought are significantly correlated with positive EA-WR values; the early stages of this drought are significantly correlated with negative NAO index values. Positive EA-WR values are also identified with meteorological droughts in 1959 and 1990-

92. During the 1951-2012 analysis period negative EA-WR values are identified during the 1995-97 and 2010-12 droughts, these droughts appear to be associated with a negative phase in the NAO.

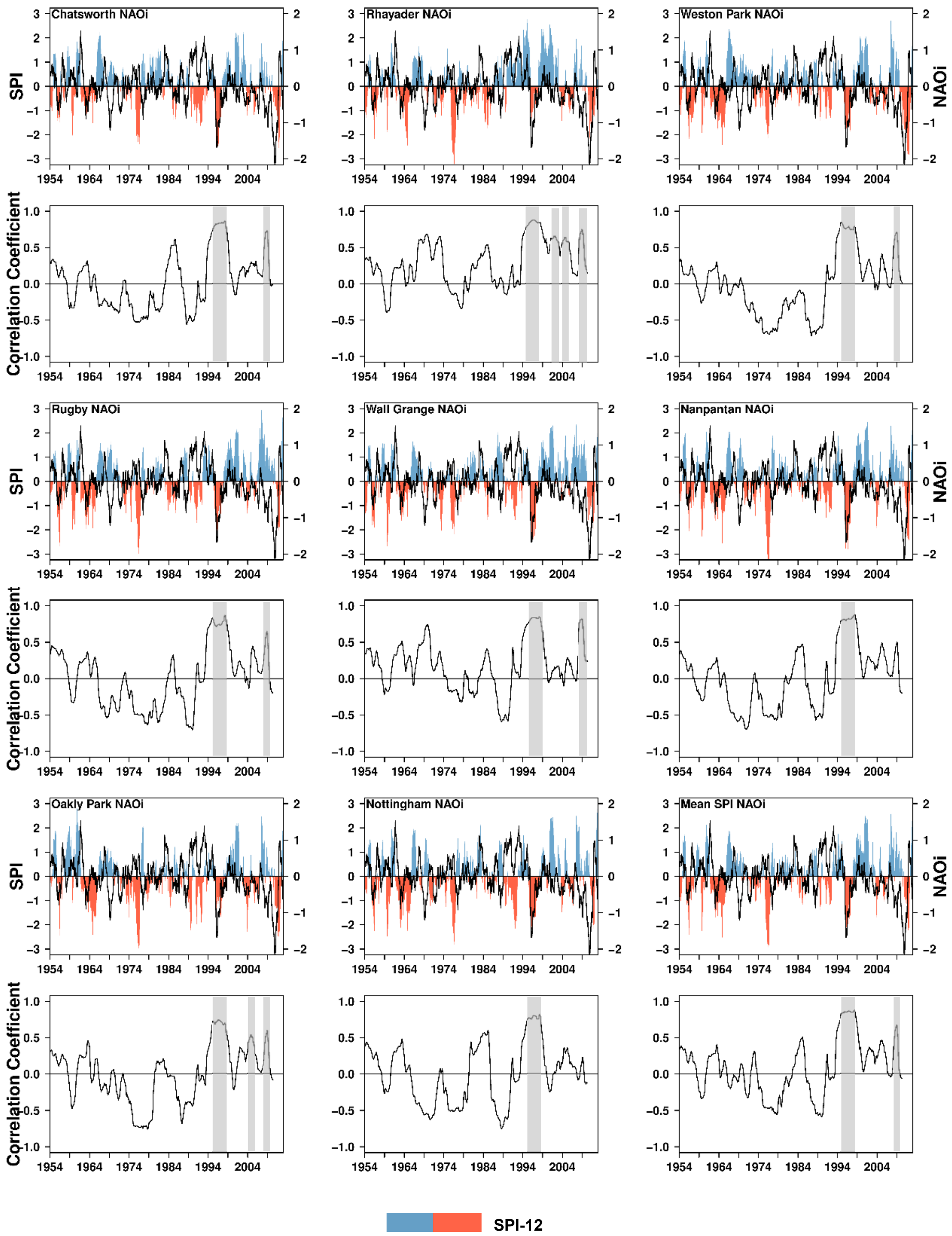

Figure 5.20: Plots for the SPI-12 and NAO index with associated 60-month moving window correlation coefficients. Grey boxes identify drought periods significantly correlated with the NAO.

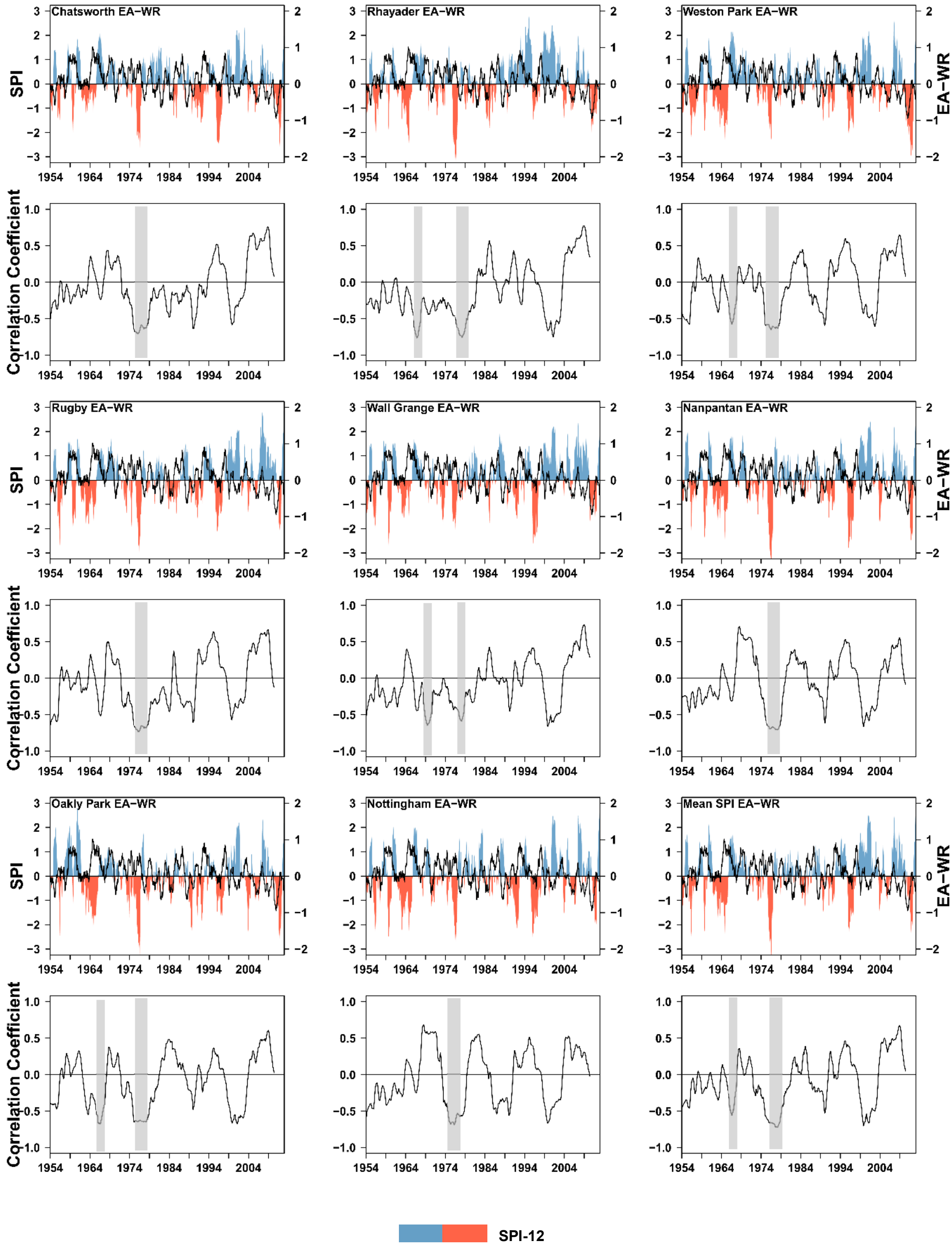

Figure 5.21: Plots for the SPI-12 and EA-WR index with associated 60-month moving window correlation coefficients. Grey boxes identify drought periods significantly correlated with the NAO.

5.4.4 Overview of the links between climatic drivers of drought and the SPI

Moving window correlation analysis between the SPI-12 and the AMO, NAO and EA-WR reveals a complex relationship between meteorological drought and large scale climate drivers. Whilst the AMO, NAO and EA-WR can all be linked to different drought events in the expected manner e.g. negative NAO positively correlated with the negative SPI-12 values in 1995-96, there are other droughts that do not appear to have links with these climate drivers. Of the five most severe droughts identified in section 4.3.17- *1862/66, 1887/89, 1921/23, 1933/35* and *1975/76,* three events are significantly correlated with large scale climate drivers at the α=0.05 level. These droughts and climate drivers are- 1862/66 is positively correlated with negative AMO, 1887/89 is positively correlated with the NAO and the 1975/76 is negatively correlated with the EA-WR. Both the 1921/23 and 1933/35 droughts have more complex links to their potential climate drivers. Whilst the 1921/23 drought occurs during a phase of negative AMO negative correlations between the AMO and SPI-12 are identified and the 1933/35 drought occurs during a positive AMO phase with weak negative correlations between the SPI-12 and the AMO. Further complexity may be added by the interrelations between the various climate drivers and drought events; for example the first year of the 1962/65 drought is linked to negative NAO and the rest of the drought event is linked to positive EA-WR values.

5.5 Summary

The results presented in this chapter use a standardised drought indicator methodology that characterises meteorological, hydrological and groundwater droughts consistently. The standardised streamflow index is computed for fifteen streamflow records across the STR and identifies a number of droughts in the 1975-2012 analysis period. Examination of the relationships between the SSI and the SPI at various accumulation periods reveals a short-term hydrological response in the STR with SPI*max* values between 1- and 5-months. Hydrological drought characteristics, particularly drought duration and frequency are variable across the STR. SSI series with the shortest (longest) SPI*max* values are associated with more (less) frequent shorter (longer) duration droughts. SPI*max* timescales are linearly correlated with catchment storage and climate characteristics. Higher BFI/BFIHOST values are generally associated with higher SPI*max* values; BFIHOST is strongly positively correlated (correlation coefficient = 0.64) with SPI*max*. SAAR is also strongly correlated with

SPI*max*, however, this is a negative correlation (-0.62); lower SAAR totals are associated with higher SPI*max* timescales.

SRI values computed for the Elan Valley and Derwent Valley reservoirs both identify a number of drought events, both reservoir groups have the same SPI*max* values at 5-months and consistent drought duration and frequency characteristics. Groundwater drought is identified using the SGI for nine groundwater water records across the major aquifer types in the STR. Analysis of frequency and duration characteristics reveals notable variation across the various aquifer types. The response of groundwater levels to meteorological condition is highly variable. SPI*max* values for the SGI are the most variable across the SSI, SRI and SGI series ranging from 4- to 44-months.

The computation of non-parametric SDI series coupling meteorological, hydrological and groundwater datasets for analysis of individual drought events provides interesting insight into the structure of droughts across the STR. This includes the characteristics of drought onset and termination; whilst some drought events show consistency in the speed and gradient of event onset or termination across the SPI, SSI and SGI series others do not. The most severe meteorological droughts do not necessarily result in the most severe hydrological or groundwater droughts. The analysis also identifies that the relationship between meteorological drought characteristics and hydrological or groundwater drought characteristics are not static, but vary between drought events. These findings indicate that the relationships between the SPI with the SSI, SRI and SGI are not straightforward.

To gain a better understanding of the hydroclimatology of drought across the STR, this chapter also presents findings for moving window correlations between the SPI-12 and three key drivers of European climate variability- AMO, NAO and EA-WR. Each of these climate drivers is linked to different drought events highlighting the complexity in the causes of meteorological drought and the importance of analysing multiple climate drivers rather than focusing on a single teleconnection pattern.

Chapter 6

Discussion

The purpose of this chapter is to review the findings of the results presented in Chapters 4 and 5 and to provide a generic evaluation of the thesis.

The following sections discuss the results presented in Chapters 4 and 5 providing an interpretation of these results, their relation with the literature, and assess whether the five objectives (section 1.2) have been achieved. This is followed by an overview of the wider significance of this work, research limitations and further work.

6.1 Use of Standardised Drought Indicators

The various examinations of drought in the STR presented in this thesis all use standardised drought indicators- the SPI, SSI, SRI and SGI; the following sub-sections discuss the appropriateness and suitability of the use of SDIs and significance of the results detailed in Chapters 4 and 5.

6.1.1 Distribution Fitting

In Chapter 4 meteorological drought characterisation and spatial and temporal coherence is investigated using the SPI based on the original computation outlined by McKee et al. (1993). Whilst the gamma distribution appears to be the most commonly used probability distribution in the computation of the SPI others have been suggested e.g. Pearson Type-III. To ascertain the best fit distribution for the rainfall datasets used in this thesis a number of probability distributions are compared. Results of this fitting (section 4.1.1) finds that there are several distributions that provide the best fit for rainfall data in the STR which appear to be influenced by the length of rainfall accumulation periods. As the accumulation period increases the number of best fit distribution increases, 1- and 3-month accumulation periods identify only two distributions compared to four distributions identified for 9-month accumulations. At the shortest accumulation period (1-month) the Weibull and Gumbel distributions are identified as best fit. At accumulations between 3- and 12-months the gamma distribution accounts for the highest proportion of best fit distributions, therefore the gamma distribution is selected for the computation of the SPI used in Chapter 4 of this thesis.

Identifying a single best fit distribution for the computation of the SPI in the STR ensures consistency in the characterisation of meteorological drought; ensuring that differences in drought characteristics are a result of variability in the rainfall data, rather than a product of probability distribution fitting. The SPI distribution fitting results presented in section 4.1.1 are similar to the findings of Stagge et al. (2015b), with Weibull the dominant best distribution for a 1-month accumulation period and the gamma, log-normal and normal distributions identified as providing the best fit distributions for accumulation periods between 3- and 12-months. Despite the identification of various best fit distributions across Europe, Stagge et al. (2015b) recommend the gamma distribution for the computation of the SPI, because of its effectiveness across a range of European climates; a finding replicated in this thesis with the dominance of the gamma distribution for rainfall accumulation periods between 3- and 12-months across the STR.

6.1.2 SPI vs. SPEI

In order to decide whether the meteorological drought characterisation in this thesis should use the SPI, SPEI or both indices; the SPI and SPEI are compared in section 4.1.2. Pearson's correlation coefficients between the SPI and SPEI for 1, 3, 6, 9 and 12-month accumulation periods at eight locations across the STR are all significantly correlated at the 0.05 level, indicating a high degree of similarity between the SPI and SPEI. Examination of drought onset and termination and drought severity shows little or no difference between the SPI and SPEI series. A number of drought events identified in the STR occur during periods of low rainfall and increased temperatures e.g. 1975-76 (Marsh and Rodda, 2011) and 1995-96 (Walker and Smithers, 1998). The consistent characterisation of these events between the SPI and SPEI indicates that the role of temperature and evapotranspiration in drought generation or persistence in the STR is not significant. Therefore, only the SPI is used in meteorological drought characterisation throughout this thesis as stated in section 4.1.2. A comparison between the SPI and SPEI by Vicente-Serrano et al. (2010) find there is little difference between the SPI and SPEI, though it should be noted that these findings are based on evapotranspiration estimates using the Thornthwaite equation, which is a useful ET estimator for historic drought characterisation, but may be less accurate than more data intensive estimation methods such as the Penman-Monteith equation (Beguería et al., 2014).

6.1.3 Nonparametric SDIs

The drought characterisation methods progress from the SPI methodology based on McKee et al. (1993) used in Chapter 4 to a nonparametric standardised drought indicator used in Chapter 5. The move to a nonparametric drought indicator methodology provides a way to consistently characterise drought for meteorological and hydro(geo)logical variables. To ensure consistency between meteorological drought characterisations in Chapters 4 and 5, SPI series at 3-, 6-, 9- and 12-month accumulation periods for both computational methods are compared in section 5.1. Results show that the nonparametric method produces consistent SPI values to the original methodology, which not only ensures consistency between meteorological drought characterisation results in Chapters 4 and 5, but it also suggests that this method can appropriately characterise hydrological and groundwater droughts (section 5.2) without the need to use a parametric fitting approach. This move to a different computation of the SPI is primarily for consistency with SSI, SRI and SGI series and not a rejection of the original SPI methodology. The use of the two computational approaches reflects the progression of the work presented in this thesis since its inception in 2012. Nonparametric SDI approaches are also used by Bloomfield and Marchant (2013); Soláková et al. (2014); Folland et al. (2015) and Farahmand and AghaKouchak, (2015). Whilst the SDI methodology used in this thesis is informed by Bloomfield and Marchant et al. (2013) it is computationally different using the Rankit normal scores transformation.

6.2 Meteorological Drought Characterisation

Meteorological drought characterisation in Chapter 4 uses both historic (8 records) and more contemporary (15 records) rainfall series to examine major drought events in the STR. Whilst the characterisation of three most recent severe droughts and their spatial and temporal variability is presented in section 4.2, it is important to develop a better understanding of the severity of historic meteorological droughts. Drought characterisation using historic rainfall datasets provides quantification of drought events that are not typically analysed; whilst there may be documented knowledge of historic drought events, such as that included in Marsh et al. (2007), this does not provide information on specific characteristics of these drought events in the STR. The examination of historic droughts also places the most recent drought events into a longer-term context. Use of the 15 more contemporary (1962-2012) rainfall datasets provides a better understanding of the spatial and temporal coherence of meteorological drought in the STR (section 4.5). This is particularly important in this region of the UK, which sits within the transitional zone between the west to east and north to south climate gradients identified across the UK (Phillips, 2013).

6.2.1 Historic Drought Characterisation

The long series characterisation using the SPI-6 and -12 identifies nineteen notable droughts between 1858 and 2012 in the STR. Meteorological drought is not a rare phenomenon, with at least one notable event experienced, based on the selection criteria, in every decade from the 1860s to the 2010s excluding the 1980s as presented in section 4.3. This indicates that major meteorological droughts with durations greater than 10-months are not a rare occurrence in the STR. This corroborates the findings of Fowler (2000), in which drought characterisation of the Yorkshire region to the northeast of the STR identifies fourteen notable droughts between 1900 and 1998; of which eight are also identified in the STR: (1) 1905-06, (2) 1933-35, (3) 1942-45, (4) 1955-57, (5) 1962-63, (6) 1964-65, (7) 1975-76 and (8) 1995-96. Pre-1900 droughts identified in both Fowler (2000) and in this thesis include 1887-89 and events that occur during the 'long drought' 1890-1910.

Characterisation of the numerous meteorological droughts in section 4.3 identifies two distinct drought typologies (based on the SPI-12) (1) long-duration, moderate-severity events and (2) moderate-duration, extreme-severity events. Long-duration, moderate-severity events include 1892-97, 1904-1908, 1942-45, 1962-65 and 1990-92. Each of these events can be broadly characterised by SPI-12 values within the 'moderate' drought classification (SPI <-1.00 to -1.49), with durations of up to 51-months. During these events single months may enter 'severe' (SPI <-1.50 to 1.99) or 'extreme' (SPI <-2.00) drought. This is in contrast with the moderate-duration extreme-severity droughts which have SPI values of <-2 for several consecutive months and are generally of shorter durations, up to 29-months.

Of the nineteen droughts characterised between 1858 and 2012, five droughts are considered as the most severe based on the lowest SPI-12 value identified at one of the eight rainfall series. These droughts can all be characterised as moderate-duration, extreme-severity events with multiple consecutive months of SPI values <-2.00 and durations of between 15- and 29-months. The most severe droughts are 1862-66, 1887-89, 1921-23, 1933-35 and 1975-76. The 1975-76 event accounts for the most severe drought for four of the eight SPI series, which supports the notion that this event be considered as the 'benchmark drought' against which other droughts are compared. The 1921-23 and 1933-35 events are also considered 'benchmark droughts' (Marsh et al., 2007); however, it is the identification of the 1862-66 and 1887-89 droughts as particularly severe which is noteworthy.

The 1862-66 drought (section 4.3.1) is the most severe drought in the Weston Park SPI-12 series; in the 12-months to November 1864 rainfall totals are 56% of the long-term average with a deficit of 315mm. Whilst not the most severe drought recorded for the Chatsworth series, this event still ranks highly, with rainfall totals in the 12-months to April 1865 accounting for 56% of the long term average. This drought does not extensively feature in other historic drought characterisations, in Marsh et al. (2007) this is not included in a summary of major droughts in England and Wales between 1800 and 2006 and does not feature as a particularly notable event in the southeast of England by Todd et al. (2013). Manley (1972) does not identify the period as notable at Manchester, with rainfall just below long-term average (~85%) in both 1864 and 1865. The only evidence in the scientific literature of this event is from Spraggs et al. (2015) who note that an extensive drought occurred in the Anglian region between 1861 and 1866. Anecdotal evidence from the Symons' Rainfall Report for 1864 notes a number of drought impacts, including:

> *"in South Wales, the drought was so severe, that many hundred hands were thrown out of employ at the iron, tinplate, and coal works, there not being water enough to keep the works going" (pp. 18, Symons, 1866).*

The drought appears to be particularly severe in the southwest of the STR:

> *"Perhaps hardly any counties showed more marked effects from the drought than Worcester, Hereford, and Gloucester." (pp. 18, Symons, 1866).*

This supports the findings that this drought is the most severe at Weston Park (located the north of Worcestershire) of the three SPI-12 series. Whilst notable at both Weston Park and Chatsworth (event minimum SPI values - 2.85 and -2.73) this drought is of only moderate severity at Rhayader (event minimum SPI value -1.85) as described in section 4.3.1. The moderate severity at Rhayader and the lack of severity in the findings of Todd et al. (2013) indicates that this event may have had a limited spatial extent. However, as both the Weston Park and Chatsworth SPI series identify this event as notably severe it is likely that drought impacts were observed across the STR; Weston Park is located in the Severn catchment, whilst Chatsworth is located in the Trent catchment. However, the lack of historic rainfall data for other sites across the STR during this period does not allow for further understanding of the spatial coverage of this event, or identification of spatial pattern of drought severity.

Presented in section 4.3.4, the 1887-89 drought is the most severe event at Wall Grange in the north of the STR. The 12-months to January 1888 account for the lowest 12-month rainfall total between 1882 and 2012 at 534mm, representing just 58% of the long term average rainfall total over 12-months between February and January (Table 4.5, section 4.3.17). Across the STR this drought ranks highly in terms of event minimum SPI values and percentage of long term average rainfall totals for January 1888. The minimum SPI values in January 1888 for the six rainfall series that capture this drought range from -2.09 to -3.26 and 12-month rainfall totals to January 1888 range from 58% to 70% of the long term average. The lowest SPI values for this event are observed in the north and north-east of the STR at Wall Grange, Chatsworth and Nanpantan within the Trent catchment. There is more information available on the 1887-89 drought than the 1862-66 event in the literature. Findings of Fowler (2000) highlight the severity of this event across the Yorkshire region, in an examination of historic drought from 1881, the 1886-88 period ranks as the most severe drought between 1881 and 1996 using the drought severity index. In a reconstruction of historic hydrological drought based on modelled streamflow, Jones and Lister (2002) find that 1887 represents the lowest annual streamflow totals in catchments in the north of England (River Derwent and River Wharfe) over a 137-year analysis period. The 1887-88 drought is not referred to in the findings of Todd et al. (2013) and Spraggs et al. (2015) for historic drought reconstructions for the south-east and east of England respectively. The findings reported in the literature combined with the results presented in this thesis suggest this drought primarily affected the north of England; a view supported by Manley (1972) with precipitation in 1887 at Manchester only representing 61% of the average rainfall.

The 1887-89 drought appears to have limited spatial extent across the STR; being most severe in the north of the region, this is further supported by Symons (1888), who discusses the severity of the drought on the Manchester region, Yorkshire and Cumbria. The SPI-12 results for the other most severe droughts (1862-66, 1921-23, 1933-35 and 1975-77) indicate greater spatial extents, with notably severe SPI values for sites located in the Severn, Wye and Trent catchments. For example, whilst the 1921-23 drought (section 4.3.6) is most severe at Chatsworth it is also notably severe at Rhayader and Oakly Park in the west of the STR and Rugby in the south-east of the STR. Similar spatial extents are also identified for the 1933-35 and 1975-77 events. Understanding the spatial extent of droughts is important when considering the use of historic climate data in water resource yield assessments, particularly in the STR which covers a large varied area including the England lowlands, Welsh uplands and Peak District. The impacts of droughts with a limited spatial extent, such as the 1887-89, is likely to produce more localised issues and have less impact on water resources across the STR, compared to spatially extensive droughts such as the 1975-76 drought. However, events with a limited spatial extent are still important, as localised impacts could be particularly significant, in smaller water resource zones that do not benefit from very large, complex water supply networks such as the Strategic Grid (section 3.1.4).

The 1975-76 drought is identified as the most severe event at four of the eight rainfall series used in the historic drought reconstructions from 1900-2012 (Table 4.5, section 4.3.17). The four SPI-12 series that identify this drought as the most severe broadly cover the STR from west to east- Rhayader and Oakly Park in the Severn and Wye catchments and Nottingham and Nanpantan in the Trent catchment. This suggests that, in terms of spatial extent, this is the most severe drought across the STR in the 1858-2012 analysis period. However, these results are potentially biased towards the post-1900 droughts, as fewer rainfall datasets are used in the characterisation of the earlier droughts e.g. 1862-66 and 1887-89, presented in sections 4.3.1 to 4.3.4.

The identification of the five most severe droughts across the STR, highlights the importance of considering a range of meteorological droughts in water resource assessments. As the STR covers such a large and diverse area of England and Wales different parts of the region experience more severe drought conditions for different events depending on where the drought is centred. For example, the 1887-89 drought appears to be most severe in the north of England based on the findings of this thesis, those of Fowler (2000) and Jones and Lister (2002). Whilst the 1933-35 drought appears to have a greater impact in the south-east of England, which is reflected in this drought being most severe at Rugby in the south-east of the STR.

6.2.2 SPI Accumulation Periods

The identification of the top five most severe droughts between 1862 and 1977 places the most recent droughts (1995-97 and 2010-12) into a longer term context. The most recent severe droughts occurring in 1995-97 and 2010-12, both resulted in water use restrictions in England but are not unprecedented events based on the SPI-12 drought reconstructions. Water use restrictions were last imposed in the STR by Severn Trent Water in 1995-96. However, analysis of the 1995-97 event based on the SPI-6 indicate that six-month rainfall totals for August 1995 are unprecedented for Rugby, Nanpantan and Nottingham in the east of the STR and Weston Park in the centre of the STR in the 1900-2012 analysis period. This highlights the rapid and dramatic onset of the 1995 drought from very wet conditions (SPI >1.5) in January and February 1995 to extreme drought in August 1995 (SPI <-2) as shown in section 4.3.15. The rapidity of drought onset for this event is also noted by Marsh (1996) and Fowler (2000).

The quick onset of this event resulted in the introduction of water use restrictions from August 1995 by many water companies across England and Wales, including Severn Trent Water. Based on the SPI-6, drought onset occurred across the STR between June and August 1995 and water use restrictions were introduced by Severn Trent Water during August 1995; there is very little lag from the onset to peak drought severity and the introduction of water use restrictions. In contrast, the lag between onset of the 1975-77 drought and the introduction of water use restrictions is much longer. Based on the SPI-6 drought onset occurs between June and September 1975, with peak severity and water use restrictions occurring in August 1976. During both of these events high temperatures would have exacerbated water demand (Marsh, 1996; Marsh and Rodda, 2011). This highlights two things, (1) it identifies a link between drought onset characteristics and the timing of a drought impact, and (2) highlights that a single SPI accumulation period for drought characterisation could mask important drought characteristics. Based on the SPI-12 the 1995-96 event appears severe, but the rapid onset is only identified using a 6-month accumulation period. This suggests that there may be a need to characterise meteorological droughts using a range of accumulation periods e.g. 3-, 6- and 12-months to adequately capture onset and termination characteristics. The rapid onset and introduction of water use restrictions of the 1995-97 drought also emphasises that a very wet preceding winter prior to a drought cannot necessarily buffer against such large rainfall deficit accumulations over such a short space of time as identified in section 4.3.15.

6.3 Spatial and Temporal Coherence of Meteorological Drought

The examination of spatial and temporal coherence of meteorological drought in the STR is undertaken in sections 4.2 and 4.5. In section 4.2, Pearson's correlation coefficient is used to identify the significance of the relationships between 14 SPI-12 series across the STR from 1962-2012. The correlation coefficients are all significant at the 0.05 level and variations in inter-site correlation appears to be a function of distance between the sites. The lowest correlation coefficient is 0.52 between Rhayader in the west of the STR and Nottingham in the east of the STR. However, correlations between Rhayader and all other sites are consistently the weakest, indicating that there may be a distinct sub-regional climatologies across the STR. To explore this further, in section 4.5, rotated PCA is used to more robustly identify any sub-regional climatologies. In order to obtain greater spatial coverage in the west of the STR an additional rainfall dataset is included in this analysis, the Clywedog rain gauge is located in the headwaters of the River Severn approximately 21km from Rhayader.

6.3.1 Identification of Sub-regional Rainfall and Drought Clusters

Rotated PCA is used to identify sub-regional clusters for both rainfall data and SPI series at 1-, 3-, 6-, 9- and 12-month accumulation periods for 15 sites across the STR. Mapped loadings of rotated PCA results indicate that there are three sub-regional rainfall clusters across the STR- (1) the far west of the STR in the Welsh uplands, (2) a central zone that includes much of the River Severn Catchment and the uplands of the Trent catchment, and (3) the eastern rainfall datasets including most of the Trent catchment and the upper River Avon catchment (see Figure 4.34). These three clusters reflect the decreasing west to east rainfall gradient across the UK. Wigley et al. (1984) identify five coherent precipitation zones across England and Wales, the STR broadly fits into two of these zones- (1) south-west England and Wales and (2) central and eastern England. However, Jones et al. (2014) identify eight sub-regional rainfall zones across England and Wales, of which the STR intersects four zones. The identification of a number of sub-regional rainfall clusters in this thesis and in Jones et al. (2014) highlights the climatic variation across the region of a single water company and exemplifies that water company regions are not necessarily related to climate regions.

In the sub-regionalisation of meteorological droughts (section 4.5) in the STR rotated PCA's identify two different cluster structures that are dependent on the length of rainfall accumulation period. Rotated PCA loadings (RPC-1 and RPC-2) for the SPI-1 and -3 identify three sub-regional drought clusters that are consistent with sub-regional rainfall clusters. As the rainfall accumulation periods increase (6- to 12-months) only two sub-regional clusters are identified; (1) Rhayader and Clywedog in the Welsh uplands, and (2) the remaining 13 rainfall datasets. The reduction in the number of sub-regional clusters as the rainfall accumulation periods increase, may result from reduced variability in the SPI values at accumulation periods greater than 6-months. Shorter SPI series (1- and 3-months) tend to exhibit greater monthly variability, whilst longer SPI series (6-months or more) exhibit less month to month variability. The identification of a western cluster (Rhayader and Clywedog) and a cluster for the rest of the STR for meteorological drought is similar to the identification of homogeneous hydrological drought regions for Great Britain (GB) identified in Hannaford et al. (2011), which identifies four homogeneous regions; (1) north-west GB, (2) north-east GB, (3) south-west GB, and (4) south-east GB. The STR intersects two of these hydrological drought sub-regions- south-west GB and south-east GB. Whilst the sub-regionalisation in this thesis and that in Hannaford et al. (2011) analyse different drought types at different spatial scales, the split of the STR into two clusters between the west and the rest of the region appears consistent.

6.3.2 Examining the Temporal and Spatial Coherence of Individual Drought Events

To investigate differences in meteorological drought between the two sub-regional clusters of individual drought events between 1962 and 2012 were examined in section 4.6. This involved analysis of SPI-12 series based on mean monthly rainfall for each cluster and SPI-12 series for 15 individual rainfall datasets distributed across the STR. Heatmaps are used to graphically represent each drought event for the sub-regional drought clusters; individual SPI series provide a useful tool in visualising drought coherence. Five droughts between 1962 and 2012 are examined- 1962-66, 1975-77, 1990-92, 1995-97 and 2010-12. Results of this analysis identify greater coherence of severe droughts and less coherence for more moderate events across the STR. For example, the variation in the timing of drought onset is larger for the 1990-92 and 2010-12 events occurring over several months (up to 19-months), whereas the variation in timing of onset occurrence is less for the 1975-77 and 1995-97 droughts (up to 6-months) at sites within the two drought clusters. In terms of drought severity, event minimum SPI values appear more coherent for the 1975-77 and 1995-97 droughts between the two sub-regional drought clusters. However, it must be noted that whilst the 1962-65 drought is categorised as a moderate severity drought this event appears to be coherent between the two drought clusters, particularly between January 1963 and February 1964 with a less coherent phase from March 1964, shown in section 4.6.1.

The variability in the coherence between droughts at the regional scale is noted by Philips and McGregor (1998), in a meteorological drought reconstruction for Devon and Cornwall,; they identify that whilst the 1992 drought appears coherent, the 1983-84 drought is not. However, the findings that the 1992 drought is coherent across Devon and Cornwall is at odds with the lack of coherence for this drought across the STR. Also at the regional scale, Fowler (2000) notes the spatial variability of meteorological droughts across Yorkshire. Of particular note, Fowler identifies large variations in drought behaviour for the 1962-65 event, which is inconsistent to the drought behaviour observed in the STR. For the 1990-92 drought (section 4.6.2), similar observations are identified between event coherence across the STR and the Yorkshire region. Fowler (2000) notes that this drought is more severe in the east of Yorkshire with little precipitation deficit in the west. This similarity suggests that the 1990-92 drought is coherent across both the STR and the Yorkshire region.

In an investigation of spatial coherence of meteorological drought across the UK using the Drought Severity Index, Rahiz and New (2012a) conclude that more severe droughts are less coherent than shorter duration moderate events. These UK scale findings are at odds with the regional scale findings for the STR presented in section 4.6; this may be a result of scale differences that mask any regional variability. This highlights the importance of regional scale analysis particularly from a water resource perspective. The identification of varying levels of drought coherence between multiple drought events across the STR emphasises the uniqueness of each drought event. From a water resource perspective, the lack of coherence between the two drought clusters for the 1990-92 and 2010-12 droughts suggests some resilience to drought impact on water supplies. For example, during the 1990-92 event drought Cluster 1 (Rhayader and Clywedog) does not enter drought based on the SPI-12 and only experiences a mild short duration (<3-months) drought based on the SPI-3 and -6. In the catchment scale analysis for the Wye catchment presented in section 5.3.6 the severity of the drought observed in the Elan Valley Reservoir Group is disproportionate to the meteorological and streamflow drought. This reservoir group supplies Severn Trent Water's strategic grid water resource zone, which is located in Cluster 2 where the 1990-92 drought is more severe. As the Elan Valley Reservoirs are located outside of the drought affected

Cluster 2 they are able to meet increased water demand associated with the drought event in the strategic grid. This can be further demonstrated by the impact of the 1990-92 drought on the Derwent Valley Reservoir Group which supplies the strategic grid and is located in Cluster 2. However, resilience associated with the identification of sub-regional drought clusters for moderate droughts like 1990-92 would not be applicable to more severe droughts, as severe droughts appear to have greater spatial and temporal coherence across the STR.

6.4 Hydro(geo)logical Drought and Drought Propagation

In Chapter 5, the non-parametric SDI method is used to compute SSI, SRI and SGI series for multiple streamflow, reservoir storage and groundwater level variables across the STR. These SDI series are correlated with the SPI at multiple accumulation periods to identify SPI*max*, the SPI accumulation period which has the highest correlation coefficient between the SPI and hydro(geo)logical SDI series. This SPI*max* value is considered to represent the hydro(geo)logical response or propagation to meteorological drought. These analyses are undertaken for the period 1975-2012 to enable the use of all streamflow, reservoir storage and groundwater level datasets in this thesis. This period captures four notable drought events- 1975-77, 1990-92, 1995-97 and 2010-12.

6.4.1 Hydrological Drought Characteristics and Catchment/Climate Controls

In section 5.2.1, the SSI is correlated with the SPI at rainfall accumulation periods from 1- to 6-months to identify SPI*max* for 15 streamflow records across the Severn, Trent and Wye catchments. Results of the correlation analysis show that SP*Imax* values range from 1- to 5-months with correlation coefficients between 0.69 and 0.78. The most common SPI*max* value is 2-months accounting for the highest SSI-SPI correlations at 8 of the 15 streamflow series and the second most common is 3-months for 4 of the 15 streamflow series. The shortest SPI*max* value (1-month) is for streamflow in the headwaters of the River Wye (55026), whilst the longest SP*Imax* (5-months) are found for the River Roden and River Tern, both tributaries of the River Severn. With SPI*max* values for all catchments less than 6-months across the STR it suggests that hydrological drought has a quick response to meteorological conditions. In a similar analysis for the UK, Barker et al. (2016) find that the most common SPI accumulation periods that have the strongest correlation with the SSI are 1-, 2- and 3-months. However, across the UK the range of SPI accumulation periods strongly correlated with the SSI range from 1- to 19-months (Barker et al., 2016). Many of the catchments with the strongest correlations for SPI-1, 2 and 3 in Barker et al. (2016) are located in the west and north of the UK, including the Welsh uplands. Strong correlations between streamflow and the SPI at accumulations between 1- and 3-months are also found in the Spanish Pyrenees by Vicente-Serrano and López-Moreno, (2005), while Szalai et al. (2000) identify similar results for small Hungarian catchments, concluding that 2- and 3-month rainfall accumulation periods are most suitable.

Across all the streamflow series used in this thesis the correlation coefficients between the SSI and the SPI at the SPImax accumulation period display a strong relationship. Pearson's correlation coefficients range from 0.69 to 0.78; this suggests that when the appropriate SPI accumulation period is identified the SPI may be a useful, robust proxy for hydrological drought. However, analysis of the relationship between SPImax and the SSI-SPI correlation coefficients reveals a strongly negative relationship (-0.76); SSI series with higher SPImax values tend to have a weaker link to the SPI. Inspection of the four SSI series with the lowest correlation coefficients reveal that three of these four series have the highest BFI/BFIHOST values (section 5.2.1). This highlights how catchment storage properties can modulate the SSI-SPI relationship, adding further complexity to the links between meteorological and hydrological drought. This suggests that the use of the SPI as a proxy for hydrological drought may be inadequate particularly in streamflow with a high base-flow component. It is also interesting to note that the correlation coefficients between the SSI and SPI for catchments with highly modified flows are not noticeably different from the 'natural' catchments based on the catchment descriptions in the National River Flow Archive (nfra.ceh.ac.uk). Correlation coefficients for the SSI-SPI relationship are the same (0.78) for a small (174km^2) upland catchment (streamflow gauge 55026) in the headwaters of the River Wye and for a large (1054km^2) catchment which includes substantial flow modifications (streamflow gauge 28085).

To gain greater insight into hydrological drought across the region, each SSI series is analysed to obtain drought frequency, duration and severity characteristics. These results show hydrological drought variability across the STR, for example, drought frequency varies from 21 to 39 drought events across the 37-year analysis period with average event durations ranging from 5- to 12-months. These findings highlight the variability in hydrological drought characteristics observed at a regional scale within Great Britain. Analysis of the relationship between SPI*max* and hydrological drought characteristics for each SSI series in section 5.2.1 shows a strongly correlated negative relationship between SPI*max* and drought frequency; drought events are more frequent in catchments with a smaller SPI*max*. The relationship between drought duration (average and maximum durations) and SPI*max* is strongly positive; droughts tend have greater duration in catchments with a larger SPI*max*. Correlation coefficients between average and maximum drought severity (the sum of SSI for the duration of a drought) and SPI*max* show strong (-0.69) and moderately (-0.54) negative relationships; more severe (more negative) drought totals are associated with higher SPI*max* (Figure 5.4). This can be summarised as catchments with higher SPI*max* tend to have less frequent, more severe, longer duration droughts. The relationship between SPI*max* and minimum drought durations is less clear. Minimum drought durations (excluding 1-month duration events) range from 2- to 5-months, indicating that short duration droughts can occur across a range of different catchments and have similar duration characteristics.

To examine the influence of both catchment properties and climate on hydrological drought response, the SPI*max* is correlated with BFI, BFIHOST and SAAR values for each catchment (Section 5.2.1, Figure 5.5). Analyses between SPI*max* and catchment storage properties show a moderate positive correlation for the BFI (0.50) and a strong positive correlation for the BFIHOST (0.64). Hydrological drought response tends to be slower in catchments with higher baseflow contributions to streamflow. However, catchments with a 2-month SPI*max* cover a range of BFIHOST values from 0.42 to 0.61, and the catchment (streamflow gauge 28046) with the highest BFIHOST value (0.65) does not have the highest SPI*max* value. This highlights that whilst there is strong positive relationship between BFIHOST and SPI*max*, other factors may influence hydrological drought response e.g. groundwater drought response. The largest SPI*max* values are for SSI series 54012 and 54012; the catchments associated with these streamflow records are underlain by a very slow responding (SPI*max* = 40-months for Heathlanes) Permo-Triassic sandstone aquifer, which is included in the SGI analysis. The aquifer underlying the catchment area for streamflow (gauge 28046) is also included in the SGI analysis and is identified as having a much quicker drought response (SPI*max* = 6-months for Alstonefield). This exemplifies that it is not only the amount of streamflow attributed to quick-flow and base-flow has a role in modulating hydrological drought characteristics, but also the hydrogeological characteristics. The hydrological drought response for 28046 being quicker than for 54012 and 54016 may also be influenced by catchment characteristics such as topography, which can speed up the rainfall to flow response (Dunn and Lilly, 2001).

The difference in correlation coefficients for SPI*max* with BFI (0.50) and BFIHOST (0.64) (section 5.2.1) may reflect the inclusion of more variables in the determination of BFIHOST compared to the BFI. The BFI is solely based on the partitioning of streamflow into quick flow and base flow, whilst the BFIHOST takes other catchment properties such a soil type into account, which also influences hydrological drought response. This is supported by the findings of Van Loon and Laaha (2015) who conclude that no single catchment storage property is dominant in controlling hydrological drought severity.

A number of studies have linked the role of catchment storage (e.g. BFI) in the modulation of hydrological drought (Zaidman et al., 2001; Fleig et al., 2011; Van Loon and Lahaa 2015; Barker et al., 2016). In an analysis of hydrological drought response across the UK, Barker et al. (2016) find that the relationship between hydrological drought response and BFI is stronger in catchments that are generally characterised by greater catchment storage (based on BFIHOST), more permeable soils and lower rainfall total; these catchments are generally located in the south and east of the UK. Catchments in the north and west of the UK with lower catchment storage, steeper slopes and higher rainfall tend to have a weaker relationship between hydrological drought response and BFI. Correlation coefficients between BFI and hydrological drought response in Barker et al. (2016) are 0.8 and 0.6 for the higher storage and lower storage catchments respectively. These findings indicate a stronger relationship between BFI and hydrological drought response to the findings presented in this thesis; this may be a result of the number and range of catchment types analysed across the UK, compared to those included in this regional scale study. The range of BFI/BFIHOST values across the catchments included in this analysis range from 0.37 to 0.79 for the BFI and 0.42 to 0.65 for the BFIHOST. This is not a broad range compared to the UK as presented in Barker et al. (2016), but there is still a notable trend.

The relationship between SPI*max* and SAAR, presented in section 5.2.1, identifies a strong negative relationship (Pearson's correlation = -0.62), lower SAAR totals are associated with a higher SPI*max*. Barker et al. (2016) reports similar findings in a UK scale analysis, noting that the link between SAAR and hydrological drought response is stronger for upland catchments in the north and west of the UK. The analysis between SAAR and SPI*max* presented in this thesis identifies that SSI series with a 2-month SPI*max* include a wide range of SAAR totals from 654mm to 1292mm. Such a range of SAAR totals with 2-month SPI*max* suggests that the role of climate is not dominant in controlling hydrological drought response across the STR. This may be a result of study scale, the STR is smaller and whilst a number of upland catchments are included in this analysis there is potentially not enough variation in the selected catchments to fully examine the role of climate in hydrological drought propagation. In an examination of the links between meteorological and hydrological drought in northern Austria, Haslinger et al. (2013) note that climate is particularly important in modulating hydrological drought in catchments with little groundwater influence.

To further examine the links between catchment and climate characteristics with drought characteristics BFIHOST and SAAR values for each catchment are correlated with drought frequency, severity and duration characteristics. Findings of this analysis shows that the links between hydrological drought characteristics and BFIHOST are generally stronger than those for SAAR across the STR. Both average and maximum drought severity and duration characteristics have a stronger relationship with BFIHOST. This is particularly notable for maximum drought duration, which has a strong correlation coefficient of 0.60 for BFIHOST and a moderate one (-0.41) for SAAR. Comparing the drought characteristics for 28031 and 28046 highlights the influence of catchment storage properties on drought characteristics, these catchments located in adjacent valleys have notable variations in hydrological drought characteristics. For example, maximum drought durations range from 9- to 20-months. Other factors that may influence the rainfall to flow relationship, such as topography can also be ruled out, as a result of the proximity of these catchments. Haslinger et al. (2013) note the importance of catchment storage properties to explain small-scale drought variability in homogenous climatic areas.

Whilst these findings suggest the catchment storage properties are slightly more dominant in the modulation of hydrological drought across the STR, the role of climate is still important, with significant correlations between all hydrological drought characteristics and SAAR. Identifying that catchment storage is more dominant than climate on hydrological drought characteristics in the STR could result from less variability in climate across the region compared to larger-scale studies that capture greater climate variability. For example, Barker et al. (2016) find that climate characteristics appear more dominant in catchments in the north and the west of the UK and catchment storage appears more dominant in the south and east of the UK. Climate variability is much greater in the analysis of Barker et al. (2016) ranging from ~500mm to ~3000mm than it is in this study, ranging from 654mm to 1688mm. At the scale of analysis in this study, the relative lack of rainfall variability compared to the whole UK highlights the importance of smaller scale influences such as catchment storage, which has been shown to have notable influence on hydrological drought characteristics in this study.

6.4.2 The Standardised Reservoir Index and Drought Characteristics

The SDI methodology is used to compute SRI series for two large reservoir groups in the STR; (1) Elan Valley, and (2) Derwent Valley (section 5.2.2). Both SRI series identify notable droughts in the 1975-2012 analysis periods, most notably the 1975-77 and 1995-97 events. Correlation analysis of the SRI series and the SPI at multiple accumulation periods identifies that both reservoir groups have a 5-month SPI*max*. Establishing the response time of these reservoirs and for streamflow within the same catchments highlights the 'smoothing' effect reservoirs have on the natural hydrological cycle to provide a consistent public water supply. Storage totals in both the Elan Valley and Derwent Valley reservoirs are partly determined by precipitation over the current month and preceding four months, whilst streamflows in the headwaters are determined by precipitation for the current and preceding month. In an examination of the links between the SPI and standardised reservoir storage volumes in the Spanish Pyrenees, Vicente-Serrano and López-Moreno (2005) establish that the SPI-8 provides the best correlation coefficient (0.59), whilst the SPI-2 and -3 are most appropriate for streamflow. Lorenzo-Lacruz et al. (2010) identify that much longer accumulation periods obtain the highest correlations (0.87) between the SPI/SPEI and standardised reservoir storages of up to 33-months, whilst reservoir inflows are best represented by an 8-month accumulation period.

Presented in section 5.2.2, the SRI-SPI*max* correlation coefficients for both reservoir groups is 0.57 and 0.55 for the Derwent Valley and Elan Valley respectively. Across the three hydro(geo)logical variables of interest these are the lowest correlation coefficients, indicating that the relationship between meteorological conditions and reservoir storage is more complex than those for streamflow and groundwater datasets used in this thesis. For example, the reservoirs are influenced by changes in water demand and controlled releases to maintain environmental flows. Both the inputs (rainfall and stream inflows) and outputs (controlled releases and water supply) influence reservoir storage. Despite this increased complexity, the relationship between meteorological conditions and reservoir storage still shows moderate positive correlation that is significant at the 0.05 level. The differences in correlation coefficients between streamflow-SPI relationships and reservoir-SPI relationships are also observed in Vicente-Serrano et al. (2005).

Drought frequency, duration and severity characteristics are consistent between both SRI series. The only notable difference between the series is for maximum drought severity, which varies from -23.7 for the Elan Valley to -31.8 for the Derwent Valley (Table 5.4). Despite the considerable geographical separation between these reservoir systems, the similarly in drought characteristics indicates that their response to meteorological drought is consistent. Both SRI series show stronger correlation coefficients for the SPI-5, indicating a reasonably quick response to meteorological conditions. The response of these reservoirs is quicker than both of the analyses for SPI-reservoir storage relationships established by Vicente-Serrano and López-Moreno (2005) and Lorenzo-Lacruz et al. (2010) at 8- and 33-months respectively. Lorenzo-Lacruz et al. (2010) attribute the long reservoir response times to a limestone geology that results in low hydrological drought response between 24 and 48 months.

Whilst the SRI is only applied to two reservoir systems across the STR, these reservoirs are particularly large and supply a number of major towns and cities across the English Midlands. The Elan Valley Group has a combined storage of approximately 99,500,000 m^3 whilst the Derwent Valley Group has a combined storage of approximately 46,000,000 m^3. The same methodology can be applied to any reservoir with sufficient data quality. Unfortunately, the data for the other reservoirs outlined in section 3.2.6 is somewhat patchy and does not allow for analysis using the SRI over the 1975-2012 period.

6.4.3 Groundwater Drought Characteristics and Geological Controls

The SGI is computed for nine groundwater boreholes within four major aquifer types across the STR. Key findings for the examination of groundwater droughts presented in section 5.2 are the notable variability in drought characteristics, which is the most variable drought type across the meteorological and hydro(geo)logical variables analysed. For example, drought frequency varies from 27 to 5 occurrences in 37-years, average groundwater drought severity ranges from -7.3 to -42.4, whilst average duration ranges from 6- to 37-months. Such a large variation in drought response is attributable to differences in geology. On a simplistic level, the karstic limestone aquifers exhibit more frequent, shorter duration, less severe droughts whilst the inter-granular Permo-Triassic sandstone aquifers present less frequent, longer duration, more severe events. Whilst there are a number of catchment characteristics e.g. soil type and hydrogeological properties that likely influence groundwater drought characteristics e.g. transmissivity, storativity and unsaturated zone thickness (as noted by Bloomfield and Marchant, 2013), there is no attempt to link these characteristics to groundwater drought behaviour in this thesis. This level of investigation falls outside the scope of this thesis and would require greater information on the specific aquifer properties at the location of the boreholes. This complexity is highlighted in Kumar et al. (2016) who note that a number of local factors are likely to influence groundwater drought response which are not readily available.

A result of the considerable variability of groundwater drought characteristics across the STR, examining the relationship between meteorological and groundwater drought requires a large range of SPI accumulation periods from 1- to 40-months. Analysis of the SGI-SPI links uses cross-correlation with lags up to 10-months rather than the standard Pearson's correlation used for the SSI and SRI. The results of this cross-correlation between the SGI and the SPI for accumulation periods between 1- and 40-months show that SP*Imax* values range from 4- to 40-months (section 5.2.3). Bloomfield and Marchant (2013) find SPI*max* variability is between 6- and 28-months for 14 observation boreholes across England and Wales. The dominant aquifer type studied in Bloomfield and Marchant (2013) is chalk, accounting for nine of the 14 datasets; this is understandable owing to the reliance on chalk aquifers for public water supply in the south-east of England. The only aquifer type included in this thesis and Bloomfield and Marchant (2013) is Permo-Triassic sandstone, Bloomfield and Marchant find SPI*max* values for this aquifer type range from 9- to 28-months; with the findings in this thesis for SPI*max* values in Permo-Triassic sandstone aquifers range from 11- to 40-months. Other aquifer types included in this work reflect the major aquifer types within the STR that provide up to 1/3 of water supplies for Severn Trent Water. Across the three types of limestone, Carboniferous and Jurassic limestone aquifers have the smallest SPI*max* values (4- to 6-months) and the only Magnesian limestone aquifer has a 12-month SPI*max*. Large variations in the SPI-SGI relationship are also observed in Kumar et al. (2016), which utilises a very large groundwater borehole dataset across the Netherlands and Germany; the range of SPI accumulation periods for maximum correlation with multiple SGI series is 3- to 36-months.

The large range of SPI*max* values found for the SGI series across the STR highlights the complexity of using the SPI at specific accumulation periods as a proxy for monitoring hydro(geo)logical droughts. This is made increasingly complex by the range of SPI*max* values observed for the same aquifer type. The range of SPI*max* for the five SGI series in Permo-Triassic sandstone aquifers is 11- to 40-months. The SGI series with the 11-month SPIm*ax* (Anthony's Cross) has notably different drought characteristics compared to the four other Permo-Triassic sandstone series. However, whilst these four SGI series still have a large SPI*max* range (27- to 40-months) the drought characteristics are rather similar, particularly for drought frequency at 5 occurrences in 37-years. It appears that at the longest SPI*max* accumulation periods (> 27-months) there is little variation in the frequency of drought occurrence. Despite this similarity in drought frequency, both severity and duration characteristics are more variable. This highlights two key points regarding the use of the SPI for groundwater drought monitoring; (1) it cannot be assumed that groundwater drought characteristics are consistent within a single aquifer type in the same region, and (2) there is little difference in groundwater drought frequency in the slowest responding (>27-months) aquifers despite varying SPI*max* values (Table 5.5).

Analysis of the relationship between SPI*max* and groundwater drought characteristics shows strong correlation coefficients between SPI*max* timescales and drought frequency, duration and severity measures. The strongest relationship is observed between SPI*max* and average event duration (0.98), overall drought duration characteristics have the strongest correlation coefficients (0.92-0.98); as SPI*max* increases so does groundwater drought duration. The SPI*max* and drought severity correlations also produce strong relationships, the larger the SPI*max* value, the greater the drought severity totals. Correlation coefficients for SPI*max* with average and minimum drought severity characteristics are -0.90 and -0.91 respectively. The relationship between maximum severity and SPI*max* is slightly weaker with a -0.78 correlation coefficient. Whilst the SPI*max* relationship shows a clear trend for greater severity totals for SGI series with larger SPI*max* values, three SGI series exhibit maximum severities that do not follow this trend. Ampney Crucis and Four Crosses appear to have much larger severity totals for their SPI*max* values, whilst Heathlanes has a relatively small maximum severity despite having the largest SPI*max*. This indicates that the trend for SGI series with a slower drought response having greater drought severity totals should not necessarily be assumed. The relationship between SPI*max* and groundwater drought frequency and duration appears to be more straightforward than for drought severity characteristics.

The correlation coefficients associated with SPI*max* for each SGI series range from 0.58 to 0.85. The strongest relationships are generally found for the longer SPI*max* values, whilst the shorter drought durations have weaker SGI-SPI relationships (section 5.2.3). Across the SSI, SRI and SGI analyses, the SPI*max*-SGI correlation coefficients show the greatest variation. This may be symptomatic of the greater variation in SPI*max* values. At shorter accumulation timescales the SPI is more variable as a result of relatively large month to month differences. As the SPI accumulation period increases, variability of the SPI decreases as month to month differences are less pronounced. This reduction in variability or 'noise' at the longer accumulation periods results in larger correlation coefficients (Altman and Krzyinski, 2015). In five SGI series the maximum SPI-SGI correlations are found with lags up to 2-months this suggests in some cases that groundwater drought response is not aligned with the meteorological drought at the specified accumulation periods and add further complexity into the use of the SPI to monitor and characterise groundwater drought. Despite the variation in correlation coefficients and the identification of 1- and 2-month lags at some sites, in the majority of SGI series there is a moderate to strong relationship with the SPI at SPI*max*. This could suggest that in absence of suitable groundwater data, the SPI at site specific accumulation periods could provide a reasonable proxy for groundwater drought. However, these findings have shown that the SPI-SGI relationship is not straightforward, therefore, the use of the SPI to monitor and characterise groundwater drought requires some caution.

6.4.4 The Relationship Between Hydrological Drought and Groundwater Drought

The examination of hydrological and hydrogeological datasets to characterise drought in the STR enables the investigation of the linkages between hydrological drought and groundwater drought. The relationship between hydrological drought response (SPI*max*) and BFI/BFIHOST identified in section 5.2.1 shows the importance of hydrogeological controls on hydrological drought. However, the range of groundwater drought characteristics across the STR identified in this thesis indicates that it is not only the proportion of base-flow to quick-flow contributions that influences hydrological drought propagation, but also the response of the underlying aquifer.

At site 28046 on the headwaters of the Dove, the SSI series has 3-month SPI*max*, which is one of the longer response times across observed in the STR despite being located in the steep, upland headwaters of the River Dove. All other sites investigated within the Dove catchment have a 2-month SPI*max*. It appears that the longer response time for the 28046 SSI is linked to a high BFI/BFIHOST value. The 28046 catchment is underlain by a Carboniferous Limestone aquifer which is examined in the SGI analysis using the Alstonefield observation borehole. The SPI*max* for the Alstonfield SGI series is 6-months and is one of the quickest groundwater response times identified within the STR. This highlights the role of groundwater contributions in buffering the onset of hydrological drought in the streamflows recorded at site 28046. This buffering effect is also identified in other catchments, the largest SPI*max* values for the SSI are for streamflow gauges 54012 and 54012 (Figure 5.2) which are underlain by a Permo-triassic sandstone aquifer with a very slow response to meteorological drought; up to 40-months measured at the Heathlanes observation borehole within the 54012 catchment. These findings highlight the complex interplay between meteorological and geological controls in the development of hydrological drought. Better understanding of the controls on hydrological drought formation requires the coupling of hydrological and hydrogeological datasets. It also demonstrates further complexities in the use of the SPI at multiple accumulation periods as a proxy for hydrological and groundwater droughts.

6.5 Examination of Drought Structure at the Catchment Scale

The examination of drought structure for individual events in six catchments across the STR provides an interesting insight into the relationships between meteorological, hydrological and groundwater drought. Key characteristics quantified in this analysis are onset and termination, total event severity and total event duration. Where multiple drought phases are identified within a drought event, the severity and duration characteristics are summed over all the phases, allowing for comparison between the different SDI variables. Drought onset and termination characteristics are quantified, using the gradient of the slope between d*ons* and d*min* for onset and d*min* and d*term* for termination (see Figure 5.11). Whilst there appears to be a high level of consistency between the drought characteristics quantified for meteorological, hydrological and groundwater droughts, this analysis provides a number of examples where the relationships between the drought types are not straightforward. The key observations noted in section 5.3 are discussed in the following sections.

6.5.1 Hydrological Drought

The most severe meteorological droughts do not necessarily result in the most severe hydrological drought; this is exemplified by the timing of the lowest SDI values for the SPI, SSI and SGI the in Dove catchment (section 5.3.2). The lowest SPI values for both the SPI-3 and SPI-6 occur during the 2010-12 drought. The lowest SSI values for the four streamflow records in the catchment are split across two separate drought events; SSI series for gauges 28008 and 28018 occur during the 1975-77 drought, for the SSI series (gauges 28031 and 28046) and the SGI all reach their lowest SDI values during the 1995-97 drought. This is also observed in the Teme catchment (section 5.3.4), the lowest SPI values and SSI values do not occur during the same drought events. This may be explained by antecedent conditions e.g. soil moisture within the catchment moderating hydrological drought severity. This inconsistency between minimum SDI values and between meteorological and hydro(geo)logical variables presents a further example that the use of the SPI as a proxy for hydro(geo)logical droughts is not straightforward. However, there are also examples of consistency between the most severe meteorological drought and most severe hydrological drought (in terms of minimum SDI value). In the Tern catchment (section 5.3.5), minimum SDI value in the 1975-2012 period for the SPI-3, SPI-6 and SSI 52012 all occur during the 1995-97 drought.

Hydrological drought characteristics are not consistent with either the characteristics identified for the SPI-3 or SPI-6 but appear to vary through time. For example, in the Dove and Leadon catchments the hydrological drought severity and duration totals for the 1975-77 drought show greater consistency with the characteristics for the SPI-6 rather than the SPI-3. As all SSI series in these catchments have 2- or 3-month SPI*max* values, it would be reasonable to assume that hydrological drought characteristics would reflect the SPI-3 characteristics rather that the SPI-6 characteristics. In other drought events there is greater consistency between the SSI and the SPI-3, this suggests that the relationship between the SSI and SPI is not static through time and a single SPI accumulation period cannot adequately represent hydrological drought.

The catchment scale analysis applied within this thesis permits examination of the relationship between meteorological and hydrological drought based on reservoir storage levels in the Derwent and Wye catchments (sections 5.3.1 and 5.3.6). Of particular note is the disproportionate drought severity for the Elan Valley SRI series compared to the SSI and

SGI series during the 1990-92 event. This is a result of increased water demand in drought cluster 2 acting as a remote driver, decreasing reservoir levels as discussed in section 6.3.2. This highlights how the inter-connected water resource system can result in drought persistence in the SRI series in the Wye catchment, which is not observed in meteorological and streamflow drought characterisations. Analysis of the SRI series in the Derwent catchment shows that the 1995-97 drought is the most severe drought in the 1975-2012 analysis period, during this event the SRI severity total (-31.82) is twice the size of the severity totals for the 1975-77, 1990-92 and 2010-12 droughts. Such a large severity total is a result of the single drought phase with no winter termination as seen in the other droughts, highlighting the importance of winter recharge in the Derwent Reservoir Group.

6.5.2 Groundwater Drought

Across the four catchments that include groundwater drought analysis some interesting observations emerge; for example, there are inconsistencies between groundwater drought and meteorological/hydrological drought characteristics. This is observed in the Derwent catchment (section 5.3.1) during the 1975-77 drought; the SGI severity total is approximately half the severity of the SPI and SSI series. However, in the other drought events characterised groundwater drought severity totals are more consistent with both hydrological and meteorological drought severity totals. This highlights that groundwater drought response may not necessarily reflect the meteorological conditions, suggesting that the use of the SPI at a specified accumulation period may not always adequately capture groundwater drought characteristics.

In both the Tern and Dove catchments the SGI series show that groundwater drought characteristics are similar between each drought quantified, despite differences observed in characteristics for the meteorological and hydrological droughts. This suggests that there is some modulating effect of the aquifers that results in similar groundwater drought response, despite each drought having unique meteorological characteristics. This is particularly notable as these SGI series are from highly contrasting aquifers, the Anthony's Cross borehole in the Leadon catchment is in a Permo-Triassic sandstone aquifer with a 12-month SPI*max,* whilst the Alstonefield borehole in the Dove catchment is situated in a Carboniferous limestone aquifer with a 6-month SPI*max*. This suggests that this similarity in groundwater drought characteristics between drought events is not specific to aquifer type.

In the Derwent catchment the second groundwater water drought phase has a steeper onset to dmin gradient than the first drought phase, as observed for the 1975-77, 1990-92 and 2010-12 droughts. This steeper onset gradient for the second drought phase may be a result of first drought phase 'priming' a quicker onset of the second phase. During each of these events there is a termination of the first drought phase, typically during winter months (November to February) which is followed by a second phase which has a steeper onset gradient. During this second phase, groundwater levels may be more responsive to meteorological drought as a result of the antecedent conditions of the first drought phase. These phases and onset characteristics are not identified in the SPI series within the Derwent catchment, illustrating that despite the identification of strong correlation coefficients between the SGI and the SPI, there are some groundwater drought characteristics that may be overlooked when the SPI is used a proxy for groundwater drought monitoring.

The lag between the onset of meteorological drought and groundwater is not consistent across all drought events. For example, in the Leadon catchment (section 5.3.3) the lag between meteorological drought onset and groundwater drought onset are not consistent between drought events; ranging from a 13-month lag for the 1990-92 drought, 7-month lag for the 1995-97, a 6-month lag between the SPI-6 and SGI for the 1975-77 drought to a 1-month lag between the SPI-6 and SGI for the 2010-12 drought. This suggests that the unique characteristics of each drought results in a different propagation response of the meteorological drought. Van Loon (2013) finds that is there is much non-linearity in the propagation of drought, which may explain the variability in hydrological and groundwater drought responses to meteorological drought that is observed in the catchment scale analysis.

Few studies use the SDI to investigate the relationship between meteorological, hydrological and groundwater drought. Kumar et al. (2016) evaluate the ability of the SPI to detect groundwater drought using results from a SGI groundwater drought characterisation, concluding that a uniform SPI cannot adequately predict groundwater droughts. The results in this study appear to support their findings. Whilst others have investigated the relationship between the SPI and SSI using correlation analyses (Vicente-Serrano and López-Moreno 2005; Lorenzo-Lacruz et al., 2010; Bloomfield and Marchant, 2013; Barker et al., 2016), these studies have not focused on the relationship between these indices to identify any consistencies between the SPI and the hydro(geo)logical drought indicators.

6.6 Linking Atmospheric Circulation Indices to the SPI-12

The final results section in Chapter 5 presents an examination of the links between the SPI and three atmospheric circulation indices- the A MO, NAO and EA-WR. Both the AMO and NAO are available from the mid-19th Century, allowing for a long-series analysis of the relationship between these indices and the SPI-12 for the three longest rainfall records in the STR from 1858-2012, and a SPI-12 series based on the mean of three rainfall records. As the EA-WR is available from 1951 a second analysis includes the examination of the relationship between the three circulation indices and the SPI-12 from 1951-2012 for eight rainfall records and a mean rainfall series calculated from these eight datasets. A moving correlation method is used with a centred 60-month window to capture the changing relationships between the circulation indices and the SPI.

6.6.1 Long Series Analysis between the SPI-12, AMO and NAO

Key findings from this long series analysis show that a number of droughts are associated with either the AMO or NAO. There is a significant positive relationship between the AMO and all four SPI-12 series during the 1862-65 drought (section 5.4.1). There is also a significant positive correlation between the AMO and the SPI-12 series for Weston Park for the 1905-07, which is a drought phase within the 'long drought' (1890-1910). Whilst there are other drought events that also occur during negative AMO phases such as the 'long drought' 1890-1910, 1921-23, 1975-77 and 1990-92 there is not a significant relationship between the AMO and SPI-12 for these events.

Whilst, negative AMO is typically associated with reduced precipitation across the UK, there are a number of drought events observed in the STR that occur during positive AMO phases; these include 1933-35, 1942-46 and 2010-12. Folland et al. (2015) note that the inter-relation between the AMO and NAO is typically characterised by negative (positive) NAO occurring with positive (negative) AMO. Based on this understanding of the inter-relation of AMO and NAO, in this analysis only the 2010-12 drought occurs during a positive AMO phase and negative NAO phase, which identifies a significant correlation between the SPI-12 and NAO. Whilst some of the most severe droughts characterised in this thesis occur during negative phases of the NAO (1862-65, 1921-23 and 1975-77), the findings presented identify no clear relationship between the AMO and incidence of meteorological drought in the STR (section 5.4.1). In an examination of the climate drivers of drought in the English lowlands during the winter half of the year, Folland et al. (2015), reach similar findings; neither negative nor positive AMO phases provide a meaningful link with drought occurrence. However, Ionita et al. (2012) conclude that variability in drought across Europe during summer months is strongly related to the previous winters SST anomalies, including the AMO. As both Folland et al. (2015) and Ionita et al. (2012) only focus on opposing half years (winter and summer) and few other studies have investigated the AMO and drought occurrence link across Europe, the potential relationship between the AMO and drought remains unclear.

The analysis between the NAO and the SPI-12 identifies four droughts that have a significant positive relationship for all four long-series SPI-12 datasets; (1) 1887-89, (2) 1901-03, (3) 1995-97, and (4) 2010-12. Each of these drought events is associated with negative NAO, which is typically linked to colder, drier winters resulting from a greater occurrence of easterly winds and anticyclones centred on the UK. Interestingly, during three of these drought events; (1) 1887-89, (2) 1995-97 and (3) 2010-12 cold, snowy winters were also experienced, emphasising the role of negative NAO phase on UK winter weather. Whilst the 1933-35 drought occurs during a negative NAO phases, overall there is no significant relationship between the NAO and SPI-12 (section 5.4.1). In a Europe-wide analysis of the relationship between the NAO and the SPI from 1900-2000, Lopez-Moreno and Vicente-Serrano (2008) find that there is a broad scale trend for positive SPI averages (wetter weather) during positive phases of the NAO. Also noted is the link between negative NAO values with winter and spring soil moisture droughts, followed by hydrological droughts during the summer and autumn in northern Europe; which leads the authors to suggest that there is some possibility to use the NAO index with the SPI to predict and monitor hydrological droughts.

The link between drought events and negative NAO phases is also identified by Wedgbrow et al. (2002) who note that negative winter NAO anomalies precede negative PDSI values and lower than average streamflows (particularly in the south-east of England). Fowler (2000) finds strong connections between winter precipitation totals and the winter NAO. Despite a broad trend between the NAO and drought noted by Lopez-Moreno and Vicente-Serrano (2008), the analysis in this thesis identifies a number of drought events that are not associated with negative NAO phases; these events include 1921-23, 1975-77 and 1990-92. This indicates that whilst there is a link between meteorological drought and negative NAO phases, the NAO represents the most important mode of climate variability (Folland, 2002); the findings (section 5.4) suggest that as all meteorological drought events cannot be attributed to the NAO alone other climatic drivers should also be considered.

The SPI-12 series for Rhayader has notably more periods of significant correlation between the negative SPI-12 values and negative NAO phases; eight periods at Rhayader, rather than the four periods identified for Chatsworth and Wall Grange. This may be a result of the westerly location of Rhayader in the Welsh uplands. Osborne and Hulme (2002) note that changes in precipitation linked to the NAO are more pronounced for the western UK, whilst Wilby et al. (1997) note that the relationship between the NAO and rainfall across the UK varies from west to east. This suggests that the link between drought events in the west of the STR and the NAO is more pronounced than for the rest of the STR. However, as a result of the long-series datasets (section 5.4.1) used in this analysis there is limited spatial coverage of the STR so this relationship cannot be fully explored, but may have important implications in water resource management planning.

6.6.2 Links between the SPI-12 and AMO, NAO and EA-WR 1951-2012

Key findings for the relationship between AMO and the SPI-12 over the 1951-2012 analysis period for eight SPI series show that there are no drought events that are significantly correlated with the AMO. However, there are a number of drought events that occur during a negative phase of the AMO between the mid-1960s and mid-1990s. As identified in the long series analysis, both the 1995-97 and 2010-12 droughts are significantly correlated with negative NAO phases. However, for two of the SPI-12 series only the 1995-97 drought is significantly correlated with the NAO- Nottingham and Nanpantan. As this analysis uses SPI-12 series with greater spatial coverage of the STR, there appears to be a broad west to east trend in the number of significantly correlated phases between negative SPI values and negative NAO values. The SPI-12 series furthest west (Rhayader) has four significantly correlated phases, whilst the SPI-12 series furthest east has only one correlated phase. This further supports the notion discussed in the previous sub-section (6.6.1) that there is a greater link between the SPI-12 and the NAO in the west of the STR.

Results for the links between the EA-WR and the SPI-12 show that two drought events are associated with significant correlations between positive EA-WR values and negative SPI-12 values; (1) 1962-65, and (2) 1975-77. Whilst the 1975-77 drought is significantly correlated with the EA-WR across all SPI-12 series, the 1962-65 drought is only significantly correlated at four of the eight site SPI-12 series and the STR mean SPI-12 series (section 5.4.2). The 1962-65 drought provides an example of a drought that is associated with two climate drivers, during the earliest stages of this event is correlated (but not significantly) with the negative NAO, whilst the later stages are significantly correlated with the EA-WR. This highlights the complexity of attribution of drought events to single climate drivers where the inter-relation between the drivers may also have an influence.

The role of the NAO in the 1995-97 drought is noted by Parry et al. (2012) and Kingston et al. (2015). Parry et al. (2012) also comments on the connection between the EA-WR and 1975-77 drought, however, only a weak relationship is established and they note that there is greater complexity in attributing the EA-WR to drought events compared to the NAO. Kingston et al. (2015) explore the relationship between the SPI-6/SPEI-6 and the NAO and EA-WR. Their analysis uses 500-hPa geopotential height fields that are akin to the NAO and EA-WR circulation anomalies. Key findings of their analysis attribute major drought events between 1959 and 1996 to climate drivers, either “Azores high” (resembles the EA-WR) or “Dipole” (resembles the NAO). The findings in this thesis are that the “Azores high” and “Dipole” drought attribution in Kingston et al., 2015 is consistent for the 1975-77 and 1995-97 droughts, whilst the “Azores high” is also attributed the 1990 drought, however, a clear driver of this event is not evident in the analysis presented in section 5.4.1.

Kingston et al. (2015) find that “Azores high” and “Dipole” drivers of drought result in different spatial configurations of drought occurrence across Europe. “Dipole” driven droughts are typically centred over northern Europe, whilst “Azores high” droughts tend to be more centred over southern Europe. However, it appears that drought occurs across some part of the UK from each of the drivers (NAO and EA-WR) based on the analysis presented in section 5.4. Meteorological drought characterisation and attribution of climate drivers to droughts in the STR show that this region is affected by droughts driven by the NAO and EA-WR. Therefore, there may be a link between the spatial variation of droughts in the STR and their associated climate driver e.g. NAO or EA-WR.

The analysis of large scale climate drivers and the SPI-12 across the STR indicates that four of the five most severe droughts between 1858 and 2012 can be linked to specific climate drivers- (1) 1862-65 (AMO), (2) 1887-89 (NAO), (3) 1921-23 (AMO, although this correlation is not significant), and (4) 1975-77 (EA-WR). Other, less severe but notable meteorological droughts are also linked to these drivers, e.g. 1995-97 and 2010-12. These findings suggest that there may be some basis for the development of monitoring and early warning systems that combine drought indices and climate indices. However, the relationship between meteorological drought and its potential climate drivers is complex and requires further investigation using a more comprehensive analysis.

6.7 Wider Significance

Whilst this thesis is highly focused on the various facets of drought with the STR, there are a number of points that have a wider significance for drought research. These include:

1) Examination of historic meteorological data places the most recent drought events into context and provides valuable insight on the characteristics of droughts not typically analysed.
2) Drought coherence at a sub-regional scale cannot be assumed, particularly when focusing on the impact of drought for water resources management decisions that require a higher resolution analysis over a particular region or sub-region.
3) Catchment scale analysis of drought structure reveals that the SPI as proxy for hydro(geo)logical drought cannot fully capture all hydrological and groundwater drought characteristics and should be used with caution.
4) Meteorological drought characterisation and attribution of climate drivers to droughts in the STR show that this region, and potentially more widely UK/Atlantic Europe, may be affected by droughts driven by both the NAO and EA-WR

6.8 Limitations and Further Work

Key limitations of the work presented in this thesis include;

1) The use of point rainfall data rather than gridded data results in a poorer spatial coverage across the STR, which makes investigating spatial variability of meteorological droughts more difficult. Gridded data would provide an improved spatial representation of rainfall distribution, however, historic rainfall data is rather sparse and a gridded dataset based on these records would be subject to considerable uncertainties at the scales examined in this thesis.
2) As noted in section 6.6, three droughts that are associated with a negative NAO phase; (1) 1887-89, (2) 1995-97 and (3) 2010-12 all include cold, snowy winters

which could exacerbate meteorological drought severity due to rain gauge under-catch.

3) The streamflow gauges selected for analysis in thesis have rather limited spatial coverage across the STR. Hydrological drought analysis is limited to a few catchments, and the centre of the region has no representation in this work. Therefore, the findings for hydrological drought characterisation may not be representative of the whole region. There may also be some bias from the inclusion of streamflow data from gauges that have substantial anthropogenic influences, however, analysis of the SPI-SSI relationship did not indicate this.
4) The use of naturalised flow data may have allowed for greater spatial coverage of the STR and flows that are free of anthropogenic activities for hydrological drought analysis, however this is not a simple process would require hydrological modelling, which itself is not free of uncertainty and does not consider the interactions between humans and water environment.
5) Whilst the analysis of the links between atmospheric circulation indices and the SPI-12 identifies a number of links with meteorological drought, the results reveal a somewhat complex relationship. The analysis used in this work provides a basic analysis, which with further time could be explored more fully, but was not a significant theme in the thesis, as such a more comprehensive analysis of this complex problem is warranted.

This thesis has revealed a number of aspects that could be addressed through further research. These are briefly outlined below.

1) The investigation of the impact of historic droughts on deployable output in other water resource zones in the STR. In this thesis only one water resource zone was used in the application of historic rainfall data, however, it would be beneficial to understand the impacts of historic droughts across the STR.
2) An analysis of the impacts felt for each of these droughts and the significance of severe droughts on communities historically, for example, how did they respond and improve their resilience by changing their behaviour?
3) Development of SDI based drought monitoring system that considers the range of hydro(geo)logical drought responses across the STR.

4) Further investigation of drought onset and termination characteristics to identify whether this can provide extra information for drought monitoring and early warning techniques based on a probabilistic methodology.
5) Further investigation of hydrological and groundwater drought processes and improved understanding of the causes of variability in the relationship between meteorological and hydro(geo)logical drought between drought events.

Chapter 7

The Implications for Water Resource Management

The purpose of this chapter is to provide an overview of the implications of this research for drought management within the STR.

As a CASE (collaborative award in science and engineering) student, a key motivation for this thesis was the potential application of the methods used and findings of this work to be useful for future drought management at Severn Trent Water. The following sections discuss the potential implications of this body of work for water resources management not only within the STR but also more widely.

7.1 Application of Historical Drought Reconstructions and Long Series Climate Data

This thesis provides a detailed characterisation and quantification of meteorological drought across the STR dating back to 1858. Whilst there are caveats in the use of historic climate data e.g. limited spatial coverage, it provides a valuable source of information on a phenomenon that is more common than expected. However, the most severe events are relatively infrequent, with five events identified over a 154-year period. The 2012-13 drought plans produced by English water companies were required to consider the impact of drought historic severe droughts from at least 1920 to 2010. Whilst this period contains a number of severe droughts, results presented in Chapter 4 shows that there are two notably severe droughts pre-1920 that rank as the most severe drought in two SPI-12 series; 1862-65 at Weston Park and 1887-89 at Wall Grange. Both of these droughts also rank highly for drought severity in other SPI-12 series in the STR (1862-65 and 1887-89 at Chatsworth, and 1887-89 at Nanpantan). The identification and characterisation of these severe events, that have not typically been included in either Water Resource Management Plans or Drought Plans, indicates that there is a need to extend the analysis periods used in these water resource assessments. Indeed, since the inception of thesis the Environment Agency have changed their guidelines for the production of Drought Plans and now state that in the testing of drought triggers should use historic data and 'the worst drought on record' should be considered (Environment Agency, 2015). However, 'the worst drought on record' is a rather broad term, and as shown in Chapter 4, there is more than one 'worst drought on record' in terms of drought severity. As the STR covers such a large area of England and Wales it appears that these past droughts have spatially variable severities, for example, the most severe drought at Wall Grange in the north of the STR is also the most severe drought experienced in the Yorkshire region (Fowler, 2000). Whilst the most severe drought at Rugby is the 1933-35 drought which was particularly severe in southern England (Marsh et al., 2007). This suggests that over the STR a range of severe droughts should be considered that encompass the most severe drought across the region. Considering such a range of severe events provides a greater robustness that cannot be captured adequately by one most severe event. Whilst Chapter 4 includes a deployable output assessment using long-series historic data for the North Staffordshire water resource zone, it would be beneficial to investigate the impacts of these pre-1920 severe droughts across all the water resource zones in the STR.

Alternative investigations of the impact of severe meteorological droughts for water company drought plans could also include the development of synthetic drought scenarios, which can be created either using scaled real events or stochastically generated. In the most recent water company drought plan guidance, the Environment Agency recommend that water companies should consider the impact of meteorological droughts that are more severe (based on rainfall totals) and longer duration than those identified within the historical record (Environment Agency, 2015). The analysis and characterisation of meteorological droughts using a long-series approach identifies a number of moderate duration, severe drought and long-duration, moderately severe droughts that could be used for the development of scaled 'real' drought scenarios to model the response a water resource system to a drought with a duration or severity that is not experienced within the historical record. The scaled drought scenarios approach is used in Watts et al. (2012) as part of drought management workshop, however, it appears that this technique is not applied in current water company drought plans across England. The use of extended historic climate datasets would also be useful in the investigation of projected reservoir levels to develop further understanding of a range of potential reservoir storages and their associated meteorological conditions for low flow, 'normal' and high flow scenarios.

7.2 Drought Management and the Use of Standardised Drought Indicators

In the UK water industry, SDIs are not typically used in either planning documents or for monitoring purposes; whilst they are not a panacea they may provide an additional metric to those already in place. A key strength of the SPI and other SDIs is their ability to consistently compare drought characteristics between sites and also between drought events. This allowed for the examination of temporal and spatial variability of meteorological droughts across the STR in Chapter 4. This examination shows that there is intra-regional variability of drought characteristics within the STR. This highlights the need to monitor meteorological drought conditions using number of rainfall records which provides good spatial coverage of the STR to adequately capture any potential variability of future droughts. Greater understanding of variability in developing droughts may be useful for focusing management decisions in specific water resource zones or areas of the STR.

In order to compute consistent SDIs for meteorological and hydro(geo)logical variables in this these, a non-parametric calculation methodology is adopted in Chapter 5. Whilst the original parametric SPI method is very commonly used for meteorological drought characterisation it is not ideal for the computation of the SRI, SSI and SGI because of the numerous 'best fit' probability distributions required for these variables, as noted by Bloomfield and Marchant (2013). Therefore, it is recommended that the non-parametric SDI calculation provides a useful method in an operational drought management setting. It allows for consistent quantification of the SPI, SSI, SRI and SGI, and does not require parametric fitting, resulting in fewer computation steps making it more efficient. The potential to monitor meteorological, hydrological and groundwater state using a consistent metric could complement current drought triggers already used by Severn Trent Water.

A clear example of the potential use of SDIs for operational drought management, is the ability to use this drought metric to compare the state of a current drought against past events characterised. This could provide useful context for communication of drought state within the STR to water industry regulators such as the Environment Agency. New guidance provided to water companies on the drought order and permit (measures which allow water companies to implement additional drought management procedures) application process by the Environment Agency (Environment Agency, 2016) state that an 'exceptional shortage of rain' must be proved. This guidance also recommends that the patterns and timings of rainfall deficits should also be considered. Whilst there are many ways to analyse and characterised meteorological drought, the SPI offers useful metric that can be used for each of these requirements specified by the Environment Agency. The use of the SPI for this purpose can also be complemented with hydro(geo)logical drought characterisations based on the SSI, SGI and SRI.

The rapid onset of the 1995-97 drought, provides a good example for the potential of meteorological drought monitoring that uses the SPI at multiple accumulation periods. As discussed in Chapter 6, the very rapid onset of this drought resulted in a hose pipe ban in August 1995 which occurred during the same month as drought onset based on the SPI-6. This highlights the inadequacy of this timescale to monitor the onset of droughts, particularly with the characteristics of the 1995-97. Meteorological drought monitoring using the SPI should probably consider the use of a range of accumulation periods e.g. 3-, 6-, 9- and 12-months not as a representation of hydro(geo)logical drought but as way to gain a better understanding of a developing drought situation. The characterisation of meteorological drought in Chapters 4 and 5 using the 3-, 6- and 12-month accumulation periods identifies how these timescales capture a range of meteorological drought behaviours.

In Chapter 5, the investigation of hydro(geo)logical drought propagation reveals a large variation in the range of hydrological and groundwater responses across the STR. These findings have two key implications; (1) the assumption that single SPI accumulation periods (e.g. SPI-6 and SPI-12) can represent hydrological drought and groundwater drought is not valid, and (2) the use of the SPI as proxy to represent hydrological and groundwater drought requires accumulation periods from 1- to 40-months which may present a challenge in the analysis and communication of drought state. Beside this complication, the catchment scale drought analysis and drought propagation investigations suggest that the use of the SPI at a range of accumulation periods as a proxy for hydrological and groundwater drought should be used with caution. The catchment scale analysis reveals a number of examples where hydrological and groundwater characteristics cannot be adequately captured by the SPI. However, in the absence of readily available hydro(geo)logical data there some value in the use of the SPI in this way.

The use of the SRI for hydrological drought analysis in reservoirs is rather limited, unfortunately the data quality for a number of the reservoirs with digitised data is not suitable for the computation of the SRI. However, SRI series constructed for the Elan Valley and Derwent Vallley Reservoir Groups show some interesting findings as presented and discussed in the previous two chapters, particularly the disconnect between drought severity in the Wye catchment compared to the reservoirs during the 1990-92 drought. There may be scope for the use of an SRI as a monitoring tool alongside the already well developed reservoir triggers than are currently used for drought monitoring and management decisions by Severn Trent Water. However, this requires further investigation SRI during drought and 'normal' conditions across each season,

7.3 Future Drought Management Considerations

Three key areas that are not directly tackled in this thesis, but are highly important in the research and management of drought are; (1) the implications of climate change, (2) UKCP09 and climate change projections and (3) an improved understanding of the socio-hydrology of this hazard.

A number of studies investigate the potential impacts of climate change on meteorological drought in the UK (Blenkinsop and Fowler, 2007; Wade et al., 2007; Vidal and Wade, 2009; Rahiz and New, 2012b). However, there appears to be a lack of consistency in the findings, in part resulting from the uncertainties associated with the use of different climate models (Watts et al., 2015). Therefore, water managers should consider a range of possible future drought scenarios focused on improving their understanding of the hydrological response of historic droughts (Watts et al., 2015).

The potential impact of climate change on water resources in England and Wales is addressed in water resource management plans (WRMPs), which set out how water companies intend to manage the balance between supply and demand over a 25-year period. The most recent WRMPs published in 2013-14 have incorporated the UK Climate Change Projections 2009 (UKCP09) based on methods outlined by the Environment Agency. Guidance on the use of UKCP09 projections within the water industry highlight the need for; (1) a risk-based approach that considers the likelihood and magnitude of different climate change outcomes that can be used to inform decision making, and (2) an evaluation of water resource systems resilience to a range of possible future climates (Environment Agency, 2013). The UKCP09 projections are used to assess impacts of climate change on water supply (DO) and demand to compute the water resource zone headroom allowance (for unavoidable uncertainties in the estimation of the supply demand balance) (Charlton and

Arnell, 2011). The WRMPs do not explicitly investigate the implications of climate change on drought characteristics, such as frequency and severity, but apply a more general approach to a changing climate over the next 25-years. Based on the findings of Blenkinsop and Fowler, (2007); Wade et al. (2007); Vidal and Wade, (2009); Rahiz and New, (2012b), the investigation of changes to meteorological drought characteristics and their implications for water resources may be problematic and requires further investigation.

The emerging field of socio-hydrology attempts to understand the complex coupled human-water systems relationship, considering the interactions and feedback between humans and the water cycle (Sivaplan et al., 2012). Whilst the need to study drought is often driven by the severe impacts it can have on society, it is typically viewed and researched with little consideration for the role of humans in the exacerbation or modulation of drought. The gaps in understanding between the drought hazard and its inter-relations with anthropogenic activities is outlined in Van Loon et al. (2016), with the conceptualisation of a drought framework, which considers the complex drivers and feedback mechanisms of drought in the Anthropocene. An improved understanding of drought with an emphasis on water resource implications requires further investigation within this human-environment framework. A key area of study which could be particularly beneficial from a water resource perspective is an improved understanding of water demand increases during a drought. As discussed in sections 6.4.2 and 6.5.1, the relationship between the SPI and the SRI is complex, being governed by meteorological inputs and water demand outputs. In the Elan Valley, there is a disconnect between the location of the reservoirs and the location of its supply zone in the Birmingham region. A better understanding of the drivers and customer perspectives of demand may provide further insight that can be included in the understanding of drought and its management.

7.4 Summary

This chapter has identified some of the ways the work completed for this thesis and its key findings could be used or implemented in an operational drought management setting. The application of historical drought reconstructions for water resource yield assessments nay be of particular use. This chapter has also touched upon future drought management considerations with a particular emphasis on the implications for climate change and a need to consider the socio-hydrology of drought. With the constant evolution of Water Resource

Management Plans and Drought Plans it may be possible apply this research through my upcoming position as a Water Resource Modeller and Hydrologist at Severn Trent Water.

Chapter 8

Conclusions

This chapter summarises the key findings of this thesis.

The work undertaken in this thesis explores the phenomenon of drought in the STR from meteorological and hydro(geo)logical perspectives. This broad-scale analysis within a single water resource region provides a detailed understanding of drought with a particular focus on the implications for water resources management.

8.1 Key Conclusions

Based on the five primary objectives (see section 1.2) these are the key conclusions:

Objective 1: Reconstruct and examine historic meteorological droughts using the Standardised Precipitation Index (SPI) from 1858 onwards and to apply a drought reconstruction in a water resources yield assessment to evaluate historic drought severity.

- Section 4.3.17 shows that droughts are not a rare phenomenon in the STR, there are 19 meteorological droughts with durations >10-months between 1858 and 2012. A notable drought occurs in every decade from the 1860s to the 2010s excluding the 1980s. Considering such long rainfall records highlights that the most recent droughts (1995-97 and 2010-12) are not unprecedented in duration or severity but they have noteworthy onset and termination characteristics.
- There are two distinctive drought typologies identified; (1) long duration, moderate severity events; and, (2) moderate duration, extreme severity droughts. Based on a SPI-12 analysis the longest duration, moderate severity events last up to 51-months with typical SPI values >-2, whilst SPI-6 analysis identifies these events often a series of shorter duration droughts. So despite their long duration they appear to have less impact on water resources.

- Based on the eight historic rainfall records used to construct the SPI-6 and SPI-12 series, the five most severe meteorological droughts are; (1) 1862-65, (2) 1887-89, (3) 1921-23, (4) 1933-35, and (5) 1975-77; this highlighting the need to consider the impact of historic droughts (pre-1920) for water resource yield assessments, extending back beyond the guidance (from-1920) provided by the Environment Agency, (2012a).
- In assessing water resource yield for a single Severn Trent Water WRZ, section 4.4, modelled results using the extended rainfall dataset (in which the most severe drought is identified outside of their 1920-2010 analysis period) do not alter the water resource zone deployable output significantly. However, the use of longer rainfall datasets increases the robustness of the analysis, as it captures more drought events, with different characteristics and it is recommended that all the Severn Trent Water WRZs should have a similar analysis.

Objective 2: Investigate the spatial and temporal coherence of meteorological drought using multiple sites across the Severn Trent Region to examine spatial and temporal variability of drought and how this would impact water resources management.

- In section 4.1 Correlation analysis of 14 SPI-12 series across the STR suggests that meteorological drought is spatially and temporally coherent. However, intra-regional drought variability is identified, particularly the timing of event onset and termination, which is likely to result in differing impacts on the water resource system.
- PCA analysis of the SPI at 1-, 3-, 6-, 9- and 12-month accumulation periods identifies two different drought cluster patterns (section 4.5). At the shortest accumulation periods (1- and 3-months) three clusters are identified, whilst the accumulation periods >6-months identify two drought clusters; (1) the Welsh uplands in the west of the STR, and (2) the remaining STR area.

In section 4.6, the analysis of the two drought clusters and each individual SPI-12 series for the major drought events between 1962 and 2012 reveals that there are phases of both coherence and variability across the STR. The most severe droughts e.g. 1975-77 and 1995-97 exhibit greater coherence, whilst the less severe events are more variable across the STR. This is exemplified by the 1990-92 drought, which only occurs in one of the two drought clusters.

Objective 3: Examine the propagation of meteorological drought into the terrestrial component of the hydrological cycle and water resource system, using a drought index approach to examine hydro(geo)logical drought responses using streamflow, reservoir and groundwater data.

- Hydro(geo)logical drought across the STR is examined using a non-parametric SDI approach to compute SSI, SRI and SGI series for various streamflow, reservoir level and groundwater datasets across the STR (section 5.2). This analysis reveals notable variation in hydrological (SSI) and groundwater drought characteristics.
- In an investigation of relationship between the SPI at various timescales the SSI, SRI and SGI identifies that SPI*max* values across these hydrological variables range from 1- to 40-months. The correlation coefficients between each of the SSI, SRI and SGI series at SPI*max* are all significant at the 0.05 level, indicating a moderate to strong relationship between meteorological and hydro(geo)logical droughts,
- Examination of the SSI-SPI relationship identifies that SPI*max* values across the 15 SSI series vary from 1- to 5-months, with 3-months the most common SPI*max*; hydrological drought has a quick response to meteorological conditions. Analysis of the links between hydrological drought response time with catchment storage and climate characteristics suggest that at this scale, catchment storage properties, rather than climate, have a more dominant role in the modulation of hydrological drought.
- The SRI-SPI relationship for two large reservoir groups identifies a consistent hydrological response to the SPI, both reservoirs have 5-month SPI*max* values with correlation coefficients between 0.55 and 0.57. These are the lowest correlation coefficients found in SPI-hydro(geo)logical SDI investigation and reflect the more complex relationship between reservoir storage, meteorological conditions and water supply demand.
- Analysis of the SPI-SGI relationship reveals a high degree of variability in groundwater drought characteristics in nine observational borehole

datasets across the major aquifer types used for water supply in the STR. SPI*max* values range from 4- to 40-months, groundwater drought response time is generally linked to aquifer type. However, there is also considerable variation within aquifer types highlighting the highly site specific response. Analysis of the links between SPI*max* and groundwater drought severity indicates a complex relationship, and the use of the SPI at specific accumulation periods as a proxy for groundwater drought may not fully capture severity characteristics.

Objective 4: explore drought structure at the catchment scale by coupling meteorological and hydro(geo)logical datasets to better understand the relationship between these drought types.

- In order to better understand the relationship between meteorological and hydro(geo)logical drought, SDI series are examined at the catchment scale for individual drought events between 1975 and 2012 (section 5.3). Six hydrological catchments across the region are included to capture a range of catchment sizes, aquifers types and the reservoir groups. Whilst consistency in drought characteristics between the SPI and the SSI and SGI is observed there are a number of examples where this is not the case.
- The relationship between the SPI and the SSI is not necessarily the same between different drought events, for example, in one drought event an SSI series may be consistent with the SPI-3, and then consistent with the SPI-6 in another. Analysis of SPI and SSI characteristics also reveals that the most severe meteorological droughts do not inevitably result in the most severe hydrological droughts.
- Analysis of the relationship between the SPI and the SGI at the catchment scale reveals that the lag between meteorological drought onset and groundwater drought onset is not always consistent between drought events. A number of the SGI series identify similar groundwater drought characteristics between different droughts regardless of the severity of the meteorological drought, indicating that groundwater droughts are modulated by geological controls.

- Key findings from this analysis indicate that use of the SPI at specific accumulation periods as proxy for hydrological and groundwater droughts is not straightforward and cannot adequately capture hydro(geo)logical drought response.

Objective 5: to examine links between the atmospheric circulation indices- (1) Atlantic Multidecadal Oscillation, (2) North Atlantic Oscillation and (3) East Atlantic-West Russia and the SPI to better understand the potential of the SPI and these atmospheric circulation indices for drought monitoring.

- The NAO is associated with a number of droughts between 1858 and 2012, these include 1887-89, 1901-03, 1995-97 and 2010-12. Each of these events show significant correlations between negative NAO and the SPI-12. There also appears to be a link between the negative NAO and the 1933-35 drought although no significant correlations are identified. However, like the AMO there are also a number of droughts that occur during positive NAO phases highlighting the potential for multiple climate drivers of drought, with these potentially non-stationary.
- Analysis between positive EA-WR phases and the SPI-12 identifies a significant relationship for the 1975-77 drought across the STR, and for the 1962-65 drought for four of the eight SPI-12 series. However, like the AMO and NAO, there are a number of droughts that occurring during the EA-WR phase that is not associated with typically drier conditions highlighting the complex relationships between these atmospheric circulation indices and meteorological drought.
- As discussed in section 6.6.2, the attribution of different meteorological droughts to the EA-WR or NAO in the STR (section 5.4.2) indicates there may be a link between the spatial variability of meteorological droughts and their associated climate driver.

8.2 Final Summary

This thesis has presented a broad-scale understanding of drought within a UK regional setting that may be applied within an operational drought management structure at Severn Water. Whilst this provides a detailed sub-regional knowledge there are general findings that have wider implications. This thesis has highlighted the importance of understanding long-term meteorological drought variability and drought coherence at the local scale, where a number of past investigations of drought in the UK have focused at the national or continental scale; in doing so this work has highlighted much greater spatial and temporal variability in droughts that previously considered. This presents a valuable and important step in understanding drought and approach and mechanisms for future drought management, not just in the STR but within other regions, highlighting the importance of local and regional investigations. This work also presents an example of the use of a consistent standardised drought indicator method coupling various meteorological and hydro(geo)logical datasets to gain a more holistic understanding of drought; providing a generic examination framework that has universal application.

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Appendices

Appendix A

Equation 1- Distribution Free CUSUM Test

$$V_k = \sum_{i=1}^{k} sgn(x_i - x_{median})$$

where

$$sgn(x) = 1 \; for \; x > 0$$

$$sgn(x) = 1 \; for \; x > 0$$

$$sgn(x) = -1 \; for \; x < 0$$

Equation 2- Mann-Kendall Trend Test

$$S = \sum_{i=1}^{n-1} [\sum_{j=i+1}^{n} sgn(R_j - R_i)]$$

where

$$sgn(x) = 1 \; for \; x > 0$$

$$sgn(x) = 1 \; for \; x > 0$$

Equation 3- Rank Difference Test

$$U = \sum_{i=2}^{n} |R_i - R_{i-1}|$$

Equation 4- Thornthwaite Potential Evapotranspiration

$$PET = 16\left(\frac{L}{12}\right)\left(\frac{N}{30}\right)\left(\frac{10T}{I}\right)^{\alpha}$$

where

$$I = \sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514}$$

T = mean monthly temperatu

L = day length

N = days in month

$\alpha = 6.75 \text{ x } 10^{-7} - 7.71 \text{ x } 10^{-5} + 1.79 \text{ x } 10^{-2}\text{I} + 0.491$

T_i = 12 monthly mean temperatures

Equation 5- Nash-Sutcliffe Efficiency (NSE

$$E = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2}$$

where

Q_m = modelled discharge

Q_o = observed discharge

Equation 6- Linear Interpolation

$$x = x_1 - (t - t_1)\left[\frac{x_2 - x_1}{t_2 - t_2}\right]$$

where

x_1 and x_2 = value of variable proceeding and preceding missing data

t_1 and t_2 = time/date of x_1 and x_2

Equation 7- K-S Test

$$D_n = \sup_x |F_n(x) - F(x)|$$

where

F_n = empirical cumulative distribution function

F = theoretical cumulative distribution function

Equation 8- A-D Test

$$A^2 = -N - S$$

where

$$S = \sum_{i=1}^{N} \frac{(2i-1)}{N} [\ln F(Y_i) + \ln(Y_{N+1-i}))]$$

Where

F = cumulative distribution function

Y_i = ordered data

Equation 9- AIC

$$\mathrm{AICD}_i = \mathrm{AIC}_i - \mathrm{AIC}_{min}$$

Equation 10- SPI Calculation

$$SPI = -\left(t - \frac{c_0 + c_1 t + c_1 t^2}{1 + \ d_1 t + \ d_1 t^2 + d_1 t^3}\right)$$

for $0 < H(x) \leq 0.5$

$$SPI = -\left(t - \frac{c_0 + c_1 t + c_1 t^2}{1 + \ d_1 t + \ d_1 t^2 + d_1 t^3}\right)$$

for $0 < H(x) < 1$

where

$t = \sqrt{ln\left(\frac{1}{(H(x))^2}\right)}$ for $0 < H(x) \leq 0.5$

where

and

c_0 = 2.515517 d_1 = 1.432788

c_1 = 0.802853 d_2 = 0.189269

c_2 = 0.01328 d_3 = 0.001308

Equation 11- Rankit Formula

$$h(x) = \ \Phi^{-1}\left(\frac{g(x) - 1/2}{n}\right)$$

where

Φ^{-1} = inverse normal cumulative distribution function

n = sample size

$g(x) = x_r$

x_r = rank of each sample

Appendix B

Code 1- Gumbel distribution functions added to allow `fitdist` function in `fitdistrplus` to fit a Gumbel distribution

```
dgumbel <- function(x,mu,s){ # PDF
  exp((mu - x)/s - exp((mu - x)/s))/s
}
pgumbel <- function(q,mu,s){ # CDF
  exp(-exp(-((q - mu)/s)))
}
qgumbel <- function(p, mu, s){ # quantile function
  mu-s*log(-log(p))
}
```

Code 2- Rankit rank-based inverse normal scores transformation function

```
Rank.it <- function(x) {
  xranks <- rank(x)
  tempp <- (xranks - 0.5)/(length(xranks))
  qnorm(tempp)
}
```

Appendix C

Catchment Scale Drought Analysis Tables

Derwent Catchment

		Gradient		Duration (months)			Severity	
Drought	**SDI**	**d_{ons} to d_{min}**	**d_{min} to d_{term}**	**t_{peak}**	**t_{term}**	**Total duration**	**d_{min}**	**SDI Total**
	SPI-3	-0.05	2.27	20	3	18	-3.06	-20.22
	SPI-6	-0.09	1.65	19	3	16	-2.54	-23.66
1975-77	SSI 28085	-0.51	0.13	7	12	14	-3.06	-20.20
	SGI p1/p2	-0.25/-1.79	1.25/0.23	7/2	3/8	11	-1.94	-10.61
	SRI p1/p2	-0.53/-0.59	0.99/0.25	6/5	4/8	14	-2.42	-18.16
	SPI-3 p1/p2	-1.33/-0.14	0.38 / 0.98	3/10	8/3	17	-2.54	-20.92
	SPI-6	-0.56	6.00E-05	6	24	25	-2.42	-24.78
1990-92	SSI 28085 p1/p2	-0.96/-0.10	0.17/0.14	4/12	8/9	22	-2.08	-21.00
	SGI p1/p2/p3	-0.69/-2.68/-0.16	0.42/1.17/0.10	5/2/7	6/2/10	18	-2.26	-20.17
	SRI p1/p2	-0.26/-0.26	0.69/0.78	8/8	4/4	11	-1.99	-16.67
	SPI-3	-0.59	0.04	6	15	17	-2.72	-21.99
	SPI-6	-0.53	0.10	7	20	24	-3.06	-31.99
1995-97	SSI 28085	-0.30	0.13	9	14	18	-2.72	-26.21
	SGI p1/p2	-0.22/-0.15	1.07/2.66	8/9	4/2	17	-2.72	-23.95
	SRI	-0.38	0.18	9	13	17	-3.06	-31.82
	SPI-3 p1/p2	-0.42/-0.52	0.64/0.11	5/6	4/11	16	-2.33	-15.94
	SPI-6 p1/p2	-0.32/-0.31	0.35/0.20	7/9	6/9	18	-2.33	-22.25
2010-12	SSI 28085	-0.16	2.72	10	2	8	-2.42	-10.20
	SGI p1/p2	-0.47/-1.43	0.33/0.32	4/3	6/8	15	-2.48	-22.77
	SRI p1/p2	-0.41/-0.34	0.59/0.38	4/6	5/6	11	-1.32	-11.28

Dove Catchment

		Gradient		Duration (months)			Severity	
Drought	**SDI**	**d_{ons}**	**d_{term}**	**t_{peak}**	**t_{term}**	**Total duration**	**d_{min}**	**SDI Total**
1975-77	SPI-3	-0.05	1.96	20	3	15	-2.72	-15.83
	SPI-6	-0.08	1.45	19	3	16	-2.54	-22.33
	SSI 28046	-0.47	0.04	7	12	14	-2.72	-22.62
	SSI 28031	-0.50	0.07	6	13	16	-2.72	-19.50
	SSI 28008	-0.57	0.10	6	13	14	-3.06	-21.57
	SSI 28018	-0.11	1.84	17	3	16	-3.06	-24.76
	SGI p1/p2	-1.36 / -1.28	0.09/0.39	3/3	11/8	19	-2.33	-22.21
1990-92	SPI-3 p1/p2	-0.67/-0.11	0.15/0.21	3/11	6/8	19	-1.70	-14.14
	SPI-6 p1/p2	-0.25/-0.30	0.39/0.10	6/6	3/16	18	-1.67	-17.50
	SSI 28046 p1/p2	-0.16/-0.20	0.34/0.26	7/10	5/7	13	-2.33	-11.03
	SSI 28031 p1/p2	-0.27/-0.33	0.61/1.40	7/8	4/3	11	-2.54	-12.80
	SSI 28008 p1/p2	-0.75/-0.29	0.16/0.32	4/8	7/6	13	-2.54	-13.28
	SSI 28018 p1/p2	-0.32/-0.30	0.55/1.35	7/8	4/3	10	-2.54	-12.18
	SGI p1/p2/p3	-2.26/-0.61/-1.20	0.29/0.17/1.21	2/5/3	8/9/3	18	-1.96	-23.10
1995-97	SPI-3 p1/p2	-0.62/-0.96	0.06/0.75	6/3	17/5	23	-2.13	-27.28
	SPI-6	-0.50	0.05	6	20	23	-2.72	-35.95
	SSI 28046 p1/p2	-0.41/-1.19	0.08/0.50	8/3	19/5	23	-3.06	-27.89
	SSI 28031 p1/p2	-0.38/-0.28	0.79/1.38	8/8	5/3	19	-3.06	-26.89
	SSI 28008 p1/p2	-0.35/-0.18	0.84/2.32	9/9	4/2	18	-2.72	-26.23
	SSI 28018 p1/p2	-0.36/-1.29	0.05/	9/3	19/5	21	-2.72	-29.21
	SGI p1/p2	-0.22/-0.57	0.38/0.70	12/5	9/4	17	-3.06	-23.16
2010-12	SPI-3 p1/p2/p3	-0.61/ -0.47/ -0.42	1.56/1.32/0.38	6/6/4	3/3/4	11	-3.06	-16.54
	SPI-6 p1/p2	-0.54/ -0.7	0.78/0.12	7/4	5/13	18	-3.06	-23.05
	SSI 28046 p1/p2	-0.20/-0.13	0.51/1.17	9/13	4/3	18	-2.19	-23.89
	SSI 28031 p1/p2/p3	-0.28/-1.23/-0.71	0.49/0.63/0.47	7/3/3	5/4/4	16	-1.99	-15.99
	SSI 28008 p1/p2/p3	-0.20/-1.15/-0.82	0.24/0.13/2.68	7/3/4	6/9/2	16	-2.33	-20.42
	SSI 28018 p1/p2	-0.24/-1.14	0.44/0.13	6/3	4/10	13	-1.74	-14.14
	SGI p1/p2/p3	-0.62/-1.4/1.57	0.35/0.35/1.31	4/3/3	5/8/4	20	-2.72	-22.11

Tern Catchment

Drought	SDI	Gradient: Onset	Gradient: Termination	Duration (months): tpeak	Duration (months): tterm	Duration (months): Total duration	Severity: dmin	Severity: SDI Total
1975-77	SPI-3	-0.07	3.27	16	2	11	-2.48	-13.08
	SPI-6	-0.08	1.32	19	3	12	-1.90	-16.46
	SSI 54012	-0.12	2.86	17	2	15	-2.33	-19.34
	SSI 54016	-0.10	3.12	17	2	15	-2.13	-19.30
	SGI	-0.10	0.02	16	35	41	-1.87	-28.42
1990-92	SPI-3 p1/p2	-1.09/-0.12	0.26/0.67	3/7	8/4	14	-1.66	-13.59
	SPI-6 p1/p2	-0.96/-0.15	0.25/0.35	4/11	9/6	16	-2.13	-15.82
	SSI 54012 p1/p2	-0.84/-0.12	0.28/0.48	4/12	8/7	23	-2.64	-23.36
	SSI 54016 p1/p2	-0.69/-0.15	0.33/0.54	5/12	7/5	14	-2.72	-18.06
	SGI	-0.05	0.06	27	26	30	-1.87	-29.90
1995-97	SPI-3	-0.72	0.03	6	23	24	-3.06	-22.64
	SPI-6	-1.22	0.05	4	23	23	-3.06	-29.89
	SSI 54012	-0.06	1.70	26	3	24	-3.06	-26.61
	SSI 54016	-0.02	0.30	26	7	28	-2.38	-24.99
	SGI	-0.10	0.06	23	25	33	-2.08	-31.98
2010-12	SPI-3 p1/p2	-0.15/-0.12	0.40/0.37	7/13	4/7	20	-2.72	
	SPI-6	-0.08	0.43	25	7	28	-2.72	-41.63
	SSI 54012 p1/p2	-0.38/-0.09	0.85/1.01	6/14	3/4	17	-2.62	-26.59
	SSI 54016 p1/p2	-0.38/-0.12	0.40/1.45	6/15	5/3	18	-2.72	-29.36
	SGI	-0.09	-	30	-	-	-2.72	-

Teme Catchment

		Gradient		Duration (months)			Severity	
Drought	**SDI**	**tons**	**tterm**	**tpeak**	**tterm**	**Total duration**	**dmin**	**SDI Total**
1975-76	SPI-3 p1/p2	-0.27/-0.16	0.64/1.23	6/10	4/4	13	-2.42	-18.07
	SPI-6	-0.13	0.08	18	4	15	-2.54	-24.52
	SSI 54008	-0.38	0.11	7	12	13	-2.33	-20.41
	SSI 54029	-0.14	4.19	18	2	15	-3.06	-23.81
1990-92	SPI-3 p1/p2	-1.70/-0.13	0.34/0.39	3/11	8/5	13	-2.72	-13.83
	SPI-6 p1/p2	-1.35/-0.17	0.44/0.93	3/10	8/4	15	-3.06	-19.77
	SSI 54008 p1/p2/p3	-0.98/-0.55/-2.21	0.29/0.60/0.41	4/3/2	8/3/7	16	-1.89	-18.23
	SSI 54029 p1/p2/p3	-0.36/-0.55/-0.34	0.65/0.27/0.36	8/4/4	5/6/7	19	-2.22	-21.69
1995-97	SPI-3 p1/p2	-0.54/-0.07	0.67/0.37	6/9	4/6	14	-2.13	-12.27
	SPI-6	-0.90	0.07	4	23	23	-1.87	-18.64
	SSI 54008 p1/p2/p3	-0.32/-0.52/-0.79	0.79/0.31/1.25	8/5/3	4/5/2	11	-2.26	-14.31
	SSI 54029 p1/p2/p3	-0.35/-0.38/-2.24	0.53/1.12/0.27	6/6/2	5/3/6	17	-2.22	-20.74
2010-12	SPI-3 p1/p2/p3	-0.70/-0.47/-0.17	0.82/1.02/1.36	4/6/9	4/4/3	18	-2.54	-20.86
	SPI-6 p1/p2	-0.40/-0.63	0.69/0.10	4/6	4/14	20	-2.72	-24.57
	SSI 54008 p1	-0.19	0.39	13	7	13	-3.06	-19.24
	SSI 54029 p1/p2/p3	-0.70/-0.65/-0.97	0.34/0.22/2.31	2/5/3	5/8/2	15	-2.11	-18.68

Leadon Catchment

Drought	SDI	Gradient		Duration (months)			Severity	
		dons	dterm	tpeak	tterm	Total duration	dmin	SDI Total
1975-77	SPI-3 p1/p2	-0.70/-0.55	0.73/0.25	4/4	4/9	11	-1.96	-16.95
	SPI-6	-0.15	0.44	13	6	14	-2.54	-21.51
	SSI 54017 p1/p2	-0.70/-0.19	1.88/1.16	4/13	2/4	14	-2.85	-25.94
	SGI	-0.34	0.42	12	8	13	-3.06	-20.55
1990-92	SPI-3 p1/p2	-2.34/-0.11	0.20/0.38	2/7	12/7	21	-2.19	-17.09
	SPI-6 p1/p2	-1.71/-0.17	0.22	2/7	12/4	17	-2.72	-17.27
	SSI 54017 p1/p2	-0.65/2.15	0.18/0.27	5/2	9/8	16	-1.84	-19.58
	SGI	-0.04	0.32	24	8	17	-1.80	-17.70
1995-97	SPI-3 p1/p2	-0.38/-0.24	2.31/0.07	6/6	2/12	15	-2.08	-19.30
	SPI-6 p1/p2	-0.78/-0.08	0.59/0.55	4/14	5/4	18	-2.08	-17.99
	SSI 54017 p1/p2	-0.23/-0.16	0.43/0.22	6/10	4/10	17	-2.13	-17.75
	SGI	-0.24	0.33	11	8	12	-1.94	-16.88
2010-12	SPI-3	-0.03	1.58	18	3	14	-2.33	-13.01
	SPI-6	-0.49	0.13	6	15	16	-2.38	-19.09
	SSI 54017	-0.08	2.31	15	2	13	-2.06	-16.59
	SGI	-0.12	0.37	18	7	19	-2.33	-28.24

Wye Catchment

Drought	SDI	dons	dterm	tpeak	tterm	Total Duration	dmin	SDI Total
1975-76	SPI-3 p1/p2	-0.47/-0.20	0.64/1.6	5/12	4/3	15	-3.06	-22.67
	SPI-6	-0.14	0.46	17	7	20	-3.06	-32.24
	SSI p1/p2	-0.33/-0.36	0.56/2.16	6/8	4/3	9	-3.06	-14.19
	SRI	-0.04	0.46	18	6	20	-2.08	-23.64
1990-92	SPI-3	-2.34	0.58	2	4	3	-1.81	-3.25
	SPI-6	-1.56	0.77	2	3	2	-1.44	-2.36
	SSI 55026	-0.76	0.93	4	3	3	-1.65	-3.76
	SRI	-0.16	0.49	11	5	9	-1.99	-11.20
1995-97	SPI-3	-0.76	0.21	5	9	10	-2.33	-8.96
	SPI-6	-0.93	0.11	3	15	15	-1.74	-13.93
	SSI p1/p2	-0.44/-0.78	0.20/0.61	6/3	10/4	16	-2.72	-14.11
	SRI p1/p2	-0.41/-0.73	0.50/0.21	9/4	7/8	18	-3.06	-24.11
2010-12	SPI-3 p1/p2/p3	-1.42/-0.29/-0.20	0.44/1.11/1.04	3/6/6	7/4/4	17	-2.02	-20.85
	SPI-6 p1/p2	-0.53/-0.41	0.04/0.53	5/5	16/4	17	-2.42	-23.88
	SSI 55026 p1/p2/p3	-0.21/-0.73/-0.89	1.92/1.04/1.14	6/3/3	2/3/4	11	-1.74	-11.54
	SRI p1/p2	-0.19/-0.29	0.58/0.83	7/7	4/4	6	-1.47	-6.01